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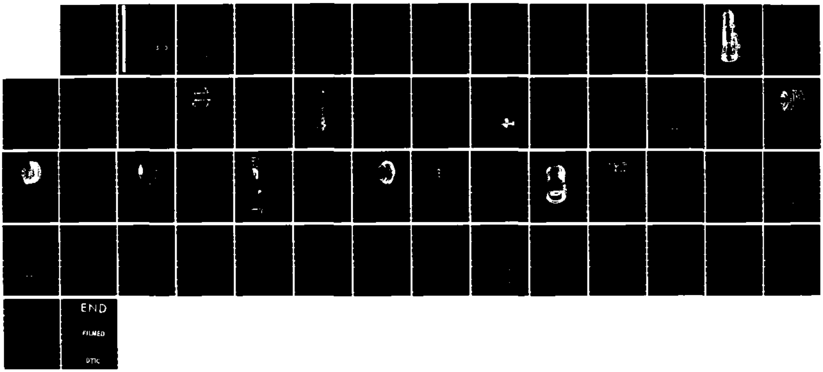

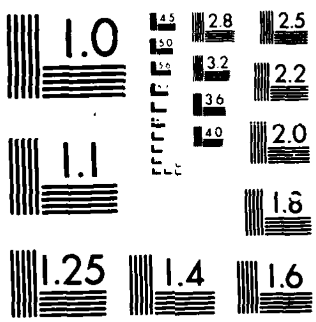

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AUSTRALIA

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

AERONAUTICAL RESEARCH LABORATORIES

MELBOURNE, VICTORIA

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Aero Propulsion Technical Memorandum 426

THE GENERAL ELECTRIC F404 - ENGINE OF THE RAAF's NEW FIGHTER

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Approved For Public Release

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SUMMARY

The F404 engine in the F/A-18 is representative of a new generation of military turbofan engines. The features of the engine that govern its performance and contribute to its maintainability are discussed. The intention is to give the non-specialist an appreciation of those factors materially affecting the operation of this type of engine.

Lecture to Melbourne Branch, ROYAL AERONAUTICAL SOCIETY
11 JUNE 1985

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CONTENTS

INTRODUCTION

The new RAAF fighter, the McDonnell Douglas F/A-18 can regularly be seen in the skies over Avalon and will be a common sight around Williamtown and Tindal Air Force Bases well into the 21st Century. This aircraft means different things to different people, even to those in the defence aerospace industry. To the pilot it is a powerful and complex flying machine full of modern gadgetry to be dutifully mastered. To the strategic planner it is a versatile and flexible weapons platform with tremendous potential. The electronics engineer can proclaim that it is a manifestation of the influence of rapidly developing micro computer technology although he will be quick to point out that the hardware is already outdated. The aerodynamicists can point to the influence of the cleanliness of the design on the manoeuvring and range performance of the aircraft. The control man will counter with the importance of the programmable, fly-by-wire control system to operation and behaviour. Materials and structures personnel will emphasise that all this is only possible through judicious choice of advanced materials and structural concepts. The propulsion engineer sees it as symbol of the subtle importance of the engine. After all, the jet engine ushered in the era of the high speed aircraft and effective airliners.

The RAAF F/A-18 Hornets are powered by two General Electric F404-GE-400 augmented turbofan engines, Figure 1. The operation of this engine can be described by referring to Figure 2. The 3-stage fan, driven by the low-pressure turbine, compresses inlet air that subsequently divides into the bypass and core flows. Variable inlet guide vanes schedule the direction of the flow into the fan as a function of rotational speed. The core flow is further compressed for entry to the annular combustor by the compressor, driven by the high-pressure turbine. Variable inlet guide and two rows of stators adjust the flow direction as a function of corrected compressor speed. After expansion through the turbines, the high temperature gas from the combustion process is mixed with the bypass air to form the high speed jet out of the exhaust nozzle. When operating in afterburning mode, the speed of this jet is increased by additional combustion in the afterburner. The exhaust nozzle has variable area to allow afterburning without materially affecting the operation of the core engine. Nozzle area is also varied during non-afterburning operation to obtain optimum performance.

This engine produces over 10,000 lb of thrust in non-afterburning operation while the maximum thrust is in the 16000 lb class. These and other leading figures are listed in Figure 3. For the convenience of those not familiar with the principal characteristics of large, military engines, the values for the Pratt & Whitney TF30, the engine in the F111c, are listed for comparison. In making such a comparison, it should be remembered that the designers of the F404 had the advantage of some fifteen years of advances in the science and technology of engine design over their TF30 counterparts. In addition, they designed against a specification that put greater accent on reliability, durability and maintainability than previously. Figure 3 shows the bald facts. The two engines are comparable in thrust even though the TF30 is 12% longer, 9% greater in diameter, 88% heavier and uses 2% more fuel.

It is natural to wonder how much this affects the operation of an aircraft like the F/A-18. The TF30 could not be fitted into this aircraft because of its size and weight so we can only arrive at a reasonable comparison by considering a hypothetical, scaled-down version of the TF30 for alternative propulsion of the F/A-18. This engine which we may call the TFH30 - the H standing for hypothetical - is presumed to work to the same cycle parameters as the parent engine but reduced in size by 12% to fit the aircraft. Its characteristics are compared with those for the F404 in Figure 4. The most noteworthy point is the reduction in thrust in non-afterburning operation by 20%. The effects of the installation of these hypothetical engines in the F/A-18 are listed in Figure 5. A comparison of this type is based upon a lot of assumptions so I hope that experts will not take issue with the detail:

the intention is to give some indication of how much effect the progress in engine design over the past fifteen years has had on the capability of fighters.

You can see that the range performance of a typical F/A-18 configuration is 6% better with the F404 than with the TFH30. 4% of this is due to the lighter weight of the F404 and 2% because of its better fuel economy, as represented by the sfc, the specific fuel consumption.

The range performance is only part of the story. Fighters are reliant upon their maximum speed to a large extent. A typical configuration of the F/A-18 with F404 would reach a maximum Mach Number about 12% greater than that achievable by the TFH30 powered version when the engines are operating in non-afterburning mode. A lot of this difference in performance is attributable to the difference in power to weight ratio of the two versions. It is shown in Figure 5 that the TFH30 powered version has a 25% lower ratio than the real version.

These figures show the superiority of the F404 over the TFH30 as a propulsor. It is expected that the F404 will also show superior operability, reliability, maintainability and durability over previous engines because of design requirements. An interesting question is what attributes of its design contribute to these qualities. I shall attempt to provide some answers to this question.

DEVELOPMENT

Before doing so it is appropriate to look at the genesis of this engine as it has an important influence on its characteristics. It started out as the YJ101, the General Electric contender for the propulsor for the US Air Force lightweight fighter. Included in the design objectives were stall-free operation, particularly under extreme transient manoeuvres, and afterburner light off and operation throughout the aircraft operating envelope. The performance was optimised for maximum thrust at subsonic altitude combat conditions while a chance was taken in deciding to use three stages in the fan rather than four because of the potential weight and cost advantages. A single-stage, low pressure turbine was selected instead of two stages for similar reasons. The Preliminary Flight Rating Test (PFRT) of December 1973 came after only 1000 hours of running, rather than the more normal 3000 hours, due to the careful definition of the development program. Seven engines were produced for flight testing in 1974 of the YF-17, the fore-runner of the F/A-18. A significant factor in the ensuring 288 flights was the absence of in-flight stalls and blowouts. This test program provided continuously recorded data on engine power usage which yielded, on analysis, information on time at temperature as well as transient throttle movements: information important in establishing life usage of engine components due to low cycle fatigue.

In the period between the YF-17 program and the selection of the F/A-18 as the new US Navy strike fighter, General Electric availed themselves of the opportunity to redesign the engine, to simplify it, to improve reliability and to improve maintainabilty. An example of what was accomplished is illustrated in Figure 6. 21 fewer parts were employed in the revised C-sump with savings in weight, cost and maintenance complexity. The US Navy then adopted a new approach in setting the requirements for the subsequent full-scale development program. In placing emphasis on operational suitability, reliability and maintainability rather than performance and weight, Figure 7, they included some new elements in the development plan:

- engine power usage definition
- 150 hr. Endurance Test
- Simulated Mission Endurance Test (SMET)
- Accelerated Service Test (AST)
- Failure Modes Effects and Criticality Analysis (FMECA)
- In-flight Engine Condition Monitoring System (IECMS)

The YF-17 flight test program had yielded the first continuously recorded data on engine power usage. The value of this in achieving the desired durability was recognised in formulating the F404 Full Scale Development (FSD) program. The Endurance Test, conducted in the altitude test cell at NAPC, was scheduled to include those regimes important to the F/A-18, including Mach 1.6 operation at 35000 feet, the regime representing maximum severity to engine hot parts. The SMET, based on design mission profiles, was used to demonstrate engine durability and was completed on schedule in July 1980. The AST encompassed 1000 hours of in-flight operation and was intended to prove reliability and maintainability whilst establishing actual mission profiles. The application of FMECA during initial design of the F404 enabled critical problems to be defined and corrected. Reliability features designed into the engine are summarised in Figure 8.

Comprehensive testing of the engine was carried out in sea-level and altitude test cells during this development program. Much of it was devoted to tuning the control system to achieve optimum engine operation and to establishing inlet/engine compatibility. Both steady and dynamic distortion patterns were generated at NAPC, the latter by the Random Frequency Generator, to simulate the flow into the engine under extreme operating conditions. However, fuel pulsing had to be employed to cause the engine to stall under these conditions and recovery was automatic. This work complemented the extensive wind tunnel testing carried out in developing the intake for the F/A-18 to produce little distortion during high angle of attack operation at low speeds while having good pressure recovery during supersonic operation. Inlet/engine compatibility has received a lot of attention following the problems encountered with the F111 in the early 1960s. The subsequent F/A-18 flight trials, beginning November 1978, confirmed that engine operation was stall free over the design manoeuver envelope. The results of these trials are summarised in Figure 9. Note that an aircraft attitude exceeding 90 degrees was temporarily attained without causing engine stall. The data on afterburner operation confirms expectations for a low bypass engine.

The AST was set back when the aircraft being used crashed at Farnborough in late 1981. However, the program recommenced with another aircraft and it has served to show how the operation of the aircraft, and the engines, can differ appreciably from what was anticipated, with important implications in relation to logistic and durability factors. For example, time at maximum temperature was found to be about 60% more than that used in the original life analyses. Further, afterburner light-ups were up 60% as well. US Navy and Canadian operational experience has tended to confirm these trends. The AST program is now being supported by a Lead the Fleet program (figure 10) in which accelerated field usage is obtained on selected engines that are closely monitored for failure, wear and life usage. This is backed by a factory program for proving the durability of components.

The F/A-18 entered service with the US Navy in early 1981, the CF18 with the Canadian Defence Forces in 1983 and the RAAF are starting pilot training at 2OCU about now. The program status is summarised in Figure 10 while that of the F404 is given in Figure 11. These figures were current last September so the engine probably has about 250,000 flight hours up now. The planned production of the F404 is shown in Figure 12. Assembly of engines down at CAC will be at a rate of about 20 per annum.

FEATURES

The F404 has a bypass ratio of 0.34:1. That is, the flow through the bypass duct is 34% of that through the core engine. A high bypass ratio improves the fuel economy, as evidenced by the high ratios of the large civil engines in such aircraft as the Boeing 747, DC10, L1011 and Airbus. Even the TF30 has a ratio of 1.1:1. Thus the bypass ratio of the F404 is low even by military standards. In fact it is often called a leaky turbojet rather than a turbofan. The consequential loss in fuel economy is offset by the rapid response to throttle operation and more reliable afterburner light up that are fundamental characteristics of low bypass engines. Figure 15 notes the expectation of General Electric of the influence of these characteristics on the operational suitability of the engine. There are reasons to

believe that these expectations are justified. These features make the F404 more suitable for fighter aircraft while the TF30 is better suited to strike aircraft where range is of prime importance.

The pressure ratio is another important parameter as it has a significant effect on the performance through its influence on the thermal efficiency. However it is limited by operability and mechanical considerations. The F404 achieves the high pressure ratio of 25:1 in 3 fan stages and 7 compressor stages, shown in Figure 16. In contrast, the TF30 needs 16 stages overall to achieve a pressure ratio of 17:1. That is, the F404 has an average stage temperature rise of 52 C compared to about 30 C for typical military engines of the previous generation. This stage temperature rise is a measure of the amount of energy the compressor blading is able to impart to each unit of flow through the compressor. It is a combination of the aerodynamic design of the blading and of the speed of rotation of the rotors. As an ex specialist in compressor aerodynamics, I found it interesting to note the developments in the aerodynamic design of both fan and compressor of the F404, including such aspects as wide chord blades and the three-dimensional, rather than quasi two-dimensional, design of the fan. Figure 17 brings this point out clearly. However, I would be giving a biased view if I did not comment upon the importance of the materials employed - largely Titanium - and of the advances in mechanical design to the attainment of this high rate of compression. To illustrate, the TF30 has a maximum tip speed of 1488 ft/sec while 1592 ft/sec is attained in the F404. Both the stage temperature rise and the centrifugal stresses are proportional to the tip speed squared!

In the design process, there is generally a requirement to compromise between the operating pressure rise and the stall margin, as illustrated in Figure 18 which depicts the speed characteristic of the fan. The selection of the stage pressure rise to match with other stages has to be a judicious choice between getting the most out of the blading and retaining a reasonable margin between the operating point and the stall line. In view of the high pressure rise per stage, it came as a surprise to find that both the fan and the compressor have good stall margins and so are able to withstand disturbances emanating from in front - the aircraft intake - and behind - pressure pulses from the afterburner - with equanimity, as demonstrated in tests, in flight trials and in operations.

The annular combustor employed is an adaption of the well proven design in the CF6 series of civil engines. Eighteen fuel nozzles supply fuel directly into the forward part of the combustion liner (Figure 19) which contains matching swirlers to facilitate atomization of the fuel. A pattern of inner and outer louvers and dilution holes in the liner causes the cooling air (Figure 20) to mix with the products of combustion.

The other main parameter of the gas turbine performance cycle is the turbine inlet temperature - the temperature of the hot efflux from the combustor. There is a requirement to maximise this value within applicable constraints in order to get high thermal efficiency and specific thrust. The major constraint is the achievement of good durability of the hot end components - nozzle guide vanes, rotor blades, disks and seals. The F404 has a turbine inlet temperature higher than any other operational military engine yet the durability of its hot end components is predicted to far exceed that for earlier engines. This is achieved by a combination of a complex cooling system for these components with the use of advanced materials - powdered super alloys and directionally solidified blading material. The cooling flow through the engine is shown in Figure 21 while Figure 22 illustrates the complexity of the cooling passages in the high pressure turbine blading. Convection, impingement and film cooling is utilised. All the blading in the turbine stages, high pressure and low pressure, stationary and rotating, are cooled, as well as rotors, cooling plates, blade and vane platforms and shrouds. To further illustrate the importance of cooling, some 11% of the air out of the compressor is used to cool the high pressure nozzle guide vanes. Because of the high pressure ratio, this air is rather hot - 520 C - so its cooling effectiveness is more dependent upon quantity than quality!

I expect that a number of you have noted that this engine is quite unusual in that it has only one high pressure turbine stage, Figure 23, and one low pressure stage, Figure 24. As mentioned earlier, this was done to keep the parts count down in order to reduce costs and improve maintainability. In part it caused a reduction in turbine efficiency with its consequential effect on performance. However, it would not have been possible without significant advances in material characterisation, mechanical design, heat transfer and turbine aerodynamics, including boundary layer development. For example, Figure 25 shows the improvement expected by substituting DSR80 for Rene 125 in the high pressure turbine blades. This is equivalent to doubling the life of these blades.

One of the most important developments has been an appreciation of the influence of low cycle fatgue on the life of such engine components as turbine rotor blading, disks and seals. This has led to the development of design methods that enable extended usage to be obtained from such components, despite the severity of their usage. For example, these turbine blades are subject to high centifugal and, in particular, thermal loads as the engine is cycled through a range of throttle settings. The condition of the blades is inferred by counts accumulated in the aircraft mission computer using an algorithm based on the temperature of the turbine exhaust gas. When the count, called Equivalent Full Thermal Cycles, reaches the prescribed limit the blades are replaced. In the case of the Rene 125 blades, this is equivalent to approximately 1000 hours of average engine operation. However, if mission severity is harsh, the prescribed number of EFTC could come up in appreciably fewer hours. It is expected that the DSR80 directionally solidified blades will have about twice the life of their predecessors.

This example is typical of the twenty odd components of the F404 whose life usage is assessed by counts calculated in the mission computer and monitored by maintenance personnel. However, most of these components have an average life of about 4000 hours which is equivalent to over 10 years of operation. I will comment further on condition monitoring shortly.

Returning to the characteristics of the engine, it is noteworthy that the sfc for non-afterburning operation is similar for the F404 and TF30. The high pressure ratio and turbine inlet temperature of the former off setting the high bypass ratio of the latter. However, the use of single stage turbines have also had their effect. The saving in weight and complexity has been obtained at the cost of a reduced turbine efficiency, with its consequent effect upon the sfc.

Turning now to the afterburner, the low bypass ratio aids light up and modulation of thrust. This is further improved by employing circumferential modulation rather than the more common radial form, which can be unreliable due to the influence of the cold bypass air. The pilot and main spray bars can be seen in Figure 26. The six pilot spray bars are equally spaced and protrube through the afterburner case and liner and extend into the flameholder. The 24 main spray bars are also equally spaced and extend radially through the afterburner case and liner and beyond the flameholder into the turbine exhaust. Fuel is pumped out of the pilot spray bars until the Light Off Detector indicates that combustion has been established when the main spray bars come into play, the number utilised being dependent upon the degree of afterburning called for by the Power Lever Angle. Fuel circulating in the main fuel manifold during non-afterburning operation cools the distributor valves, so reducung the fill time when afterburner operation is initiated.

As noted earlier, the nozzle opens up with the degree of afterburning. This is just one function of the control system which consists of a hydro-mechanical unit for control at powers less than Intermediate Rated Power (IRP), maximum non-afterburning operation. For IRP or afterburning operation, the Electronic Control Unit takes over. These units are mounted on the lower front of the engine. Figure 27 shows the layout as viewed from underneath. In this way the infeasible complexity of a full authority hydro-mechanical system in this type of variable geometry engine is avoided. Sufficient research has been done on Full Authority

Digital Electronic Control (FADEC) systems to indicate that they will be employed on future engines. However, at the time of the F404 development the reliability of electronic control units in the harsh environment on the engine casing was insufficiently proven: the hydro-mechanical unit provides a get-home capability in the event of failure of the ECU.

Some functions carried out by the control system are:

- limitation on corrected fan speed to prevent stall margin erosion
- flow restriction in supersonic flight to maintain intake performance
- fuel dip and variable geometry resetting during rocket firing
- scheduling of nozzle area to limit turbine inlet temperature
- scheduling fuel flow to limit maximum fan speed
- limiting back pressure on core engine during afterburner operation
- limiting maximum and minimum combustor casing pressures
- scheduling fuel flow for engine acceleration and deceleration

The main control operating modes in both dry and afterburning operation are shown in Figure 28. Figure 29 shows the scheduled variation at IRP of exhaust gas temperature (T5) and fan speed (N1) with inlet temperature (T1) to prevent stall margin erosion for T1 less than 440 deg R, to limit compressor maximum pressure at low altitudes between 410 and 530, to limit the turbine inlet temperature between 500 and 650 and to limit actual fan speed between 570 and 620.

To a large extent, the role of material properties and structural design concepts have only been implied in examining the features of this engine. These factors are summarised in Figures 30 and 31 which serve to illustrate the range of materials required to meet the varying, stringent requirements and to highlight some of the structural features.

OPERATION

The driver of a motor car generally expects to be able to ignore the engine of his vehicle. This is also a desirable feature for the fighter pilot. He would like to be able to use the throttle to assist in the manoeuvring of his aircraft without having to bear in mind operability limitations. The F404 is not yet fully proven but there is reason to believe that it meets the requirements listed in Figure 32. It is certainly a very responsive engine and the features built into its control system ensure that it will not have the problems in operation in the high-altitude, cold conditions over Darwin that have characterised the Atar in Mirage. Figure 33 shows the operating mode of the engine at IRP under the 1% extreme conditions at Darwin. Under cold conditions at altitude - Darwin and Panama have the coldest altitude conditions in the world - the corrected fan speed is limited to 104.4% for low Mach Numbers and reduces for the higher speeds. During hot day operation at low level, the limiting factor is turbine inlet temperature for all practical speeds.

This engine is designed for On Condition Maintenance, a concept defined in Figure 34. It is a novel concept for the RAAF. It embraces an In-flight Engine Condition Monitoring (IECMS) - Figure 35 - to provide data to assess the life usage of engine components due to low cycle fatigue, the performance status of the engines and the cause of exceedances of engine parameters. The RAAF have contracted CAC to put into place a Maintenance Data & Service Life Monitoring System (MD&SLMS) to process this monitoring data to provide meaningful information to the maintenance and engineering personnel. ARL are involved in the definition and proving of procedures to be incorporated in this system.

The information extracted in the MD&SLMS from the IECMS data will supplement information on the condition of the engines provided by:

- borescope inspections
- analysis of the debris on chip detectors
- vibration signatures
- spectrometric oil analysis

Figure 36 shows the number of borescope ports available. Most of these are accessible with the engine installed in the aircraft. The location of the chip detectors is shown in Figure 37 while Figure 38 shows the location of vibration accelerometers on the engine for testing in a cell. The one marked ECMS is also on the installed engine and serves to give warning of excessive vibration in flight.

The maintainability of the engine is further facilitated by its modular construction. Figure 39 lists the potential advantages while Figure 40 depicts the six modules. The impact of modular maintenance can be expected to vary from user to user due to the different parameters in the logistic relations.

CONCLUSION

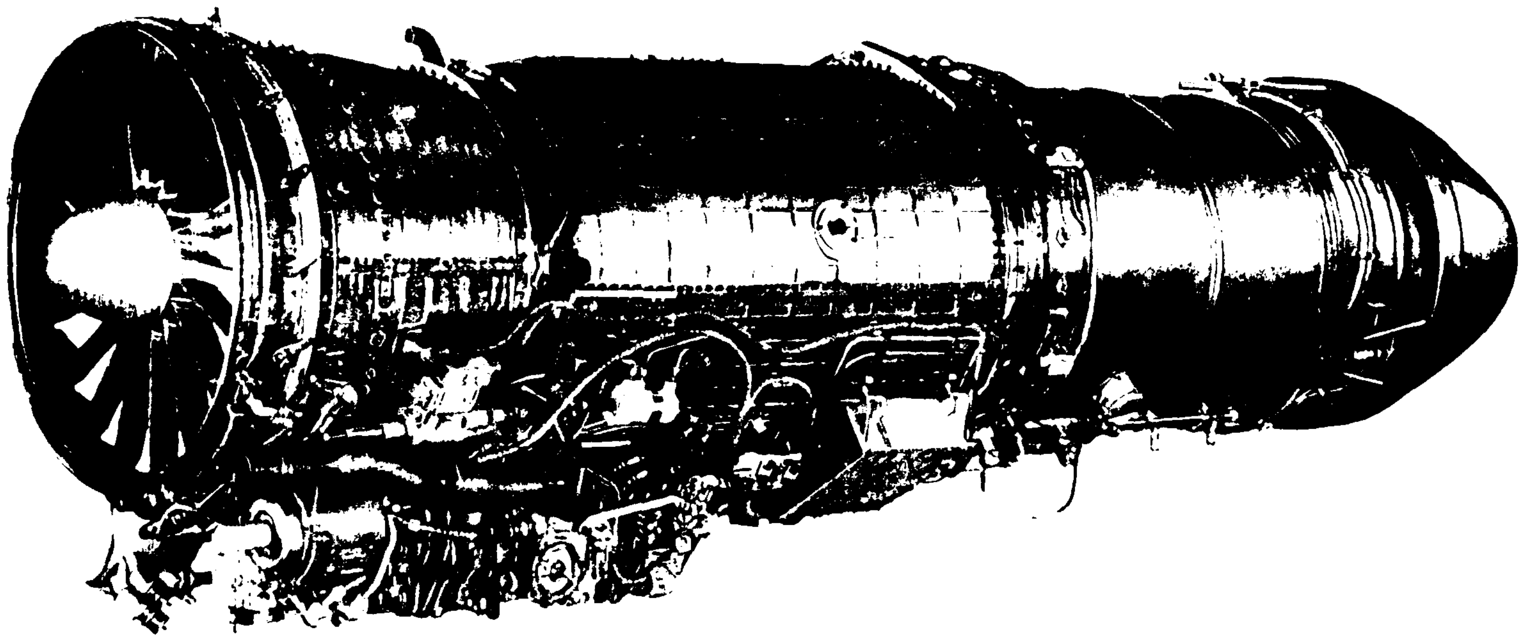
The F404 is a relatively new engine. As it has only about 250,000 hours up, it has a long way to go before it reaches maturity at one million hours. Nevertheless, the tasks being dealt with in the Component Improvement Program seem to indicate that it does not suffer any of the major, fundamental problems that have so inhibited earlier engines. There is good reason to believe that it will set new standards for military engines as regards operability, availabilty, reliability and maintainability. However, there is no reason to believe that it will be exceptional in that regard. Newer engines are predicted to follow this improved trend.

I will be interested to hear lectures in due course from RAAF and CAC personnel on experience in operating and maintaining this engine. Certainly there is much to be learnt about engine operation and its influence on maintenance from thge vaste amount of condition monitoring data being acquired through the MD&SLMS. Doubtless there will also be problems but I will be surprised if the overall view is unfavourable.

ACKNOWLEDGEMENTS

Aircraft Engine Business Group, General Electric Company supplied most of the information used in this lecture, which was authorised by the Director, Aeronautical Research Laboratories.

F404-GE-400 Augmented Turbofan Engine



• Thrust	16,000 Lb	• Bypass Ratio	0.34
• SFC Max A/B	1.85 Lb/Hr/Lb	• Weight	2,180 Lb
• SFC IRP	0.81 Lb/Hr/Lb	• Length	159 In.
• Airflow	142 Lb/Sec	• Diameter	35 In.

FIG. 1

F404-GE-400 Engine

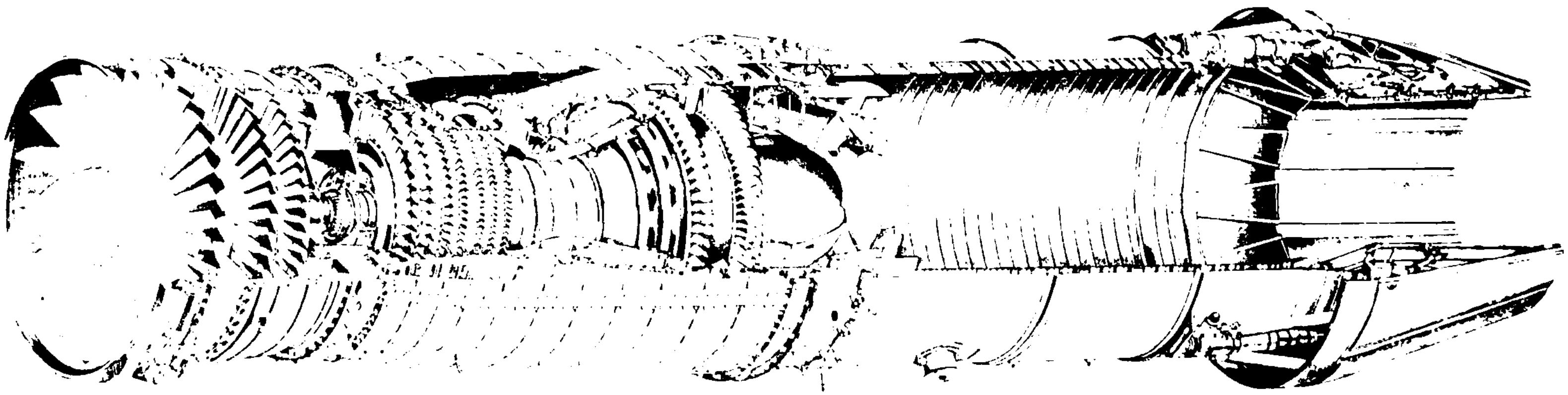


FIG. 2

	F404-GE-400 F404-GE 400	TF30 P 3	
LENGTH, IN.	159	178	(+12%)
DIAMETER, IN.	35	38	(+9%)
WEIGHT, LB.	2180	4100	(+88%)
THRUST/WEIGHT	7.3	4.9	(-67%)
MASS FLOW, LB/SEC.	142	240	(+69%)
BY-PASS RATIO	.34	1.1	
PRESSURE RATIO	25	17	
TURBINE INLET TEMPERATURE, C	1390	1270	
THRUST, MAX. A/B	16000	20000	(+25%)
" , MAX. NON-A/B	10600	10750	(+1%)
SFC, MAX. A/B, LB/HR/LB.	1.84	1.80	(-2%)
", MAX. NON-A/B "	0.78	0.80	(+2%)
FAN-STAGES	3	3	
PRESSURE RATIO	4.1	2.0	
SPEED, RPM	13270	9500	
COMPRESSOR-STAGES	7	6 + 7	
PRESSURE RATIO	6.0	8.5	
SPEED, RPM	16810	9500, 14500	

FIG. 3

	F404-GE-400	TFH-30	
LENGTH, IN.	159	159	
DIAMETER, IN.	35	34	(-3%)
WEIGHT, LB.	2180	2908	(33%)
THRUST/WEIGHT	7.3	5.5	
MASS FLOW, LB/SEC.	142	191	(35%)
BY-PASS RATIO	.34	1.1	
PRESSURE RATIO	25	17	
TURBINE INLET TEMPERATURE, C.	1390	1270	
THRUST, MAX. A/B	16000	15900	(-1%)
" , MAX. NON-A/B	10600	8550	(-20%)
SFC, MAX. A/B, LB/HR/LB	1.84	1.80	(-2%)
", MAX. NON-A/B, "	0.78	.80	(+2%)
FAN-STAGES	3	3	
PRESSURE RATIO	4.1	2.0	
SPEED, RPM	13270	10640	
COMPRESSOR-STAGES	7	6 + 7	
PRESSURE RATIO	6.0	8.5	
SPEED, RPM	16810	16240	

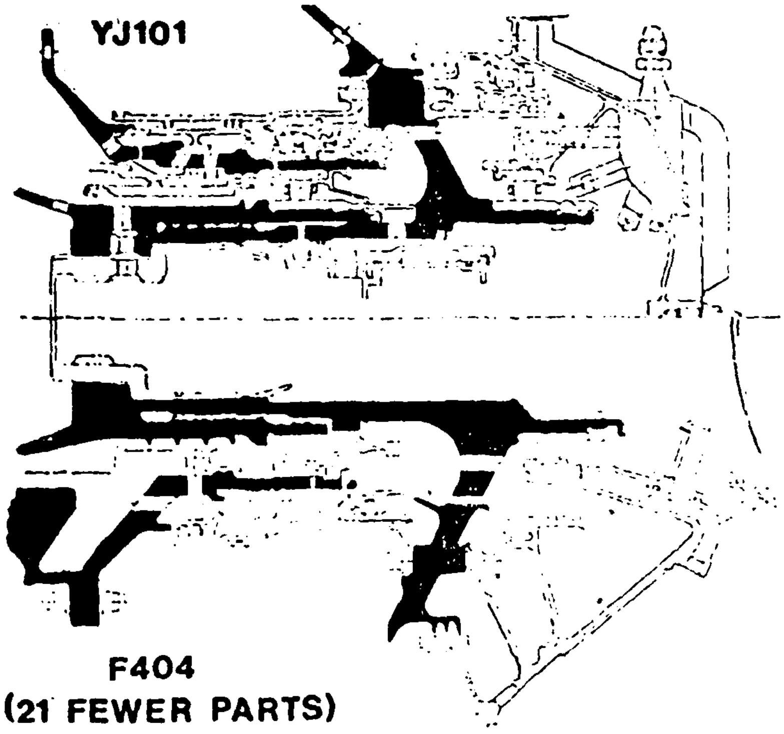
FIG. 4

HYPOTHETICAL PERFORMANCE OF F/A-18 WITH 2 x TFH30

(COMPARISON WITH F/A-18 WITH 2 x F404)

THRUST/WEIGHT	-25%
RANGE PERFORMANCE	-6%
DUE TO ENGINE WEIGHT	-4%
DUE TO SFC	-2%
MAXIMUM MACH NUMBER	-12%

FIG. 5



C-Sump Design Comparison

FIG. 6

Design/Development Emphasis

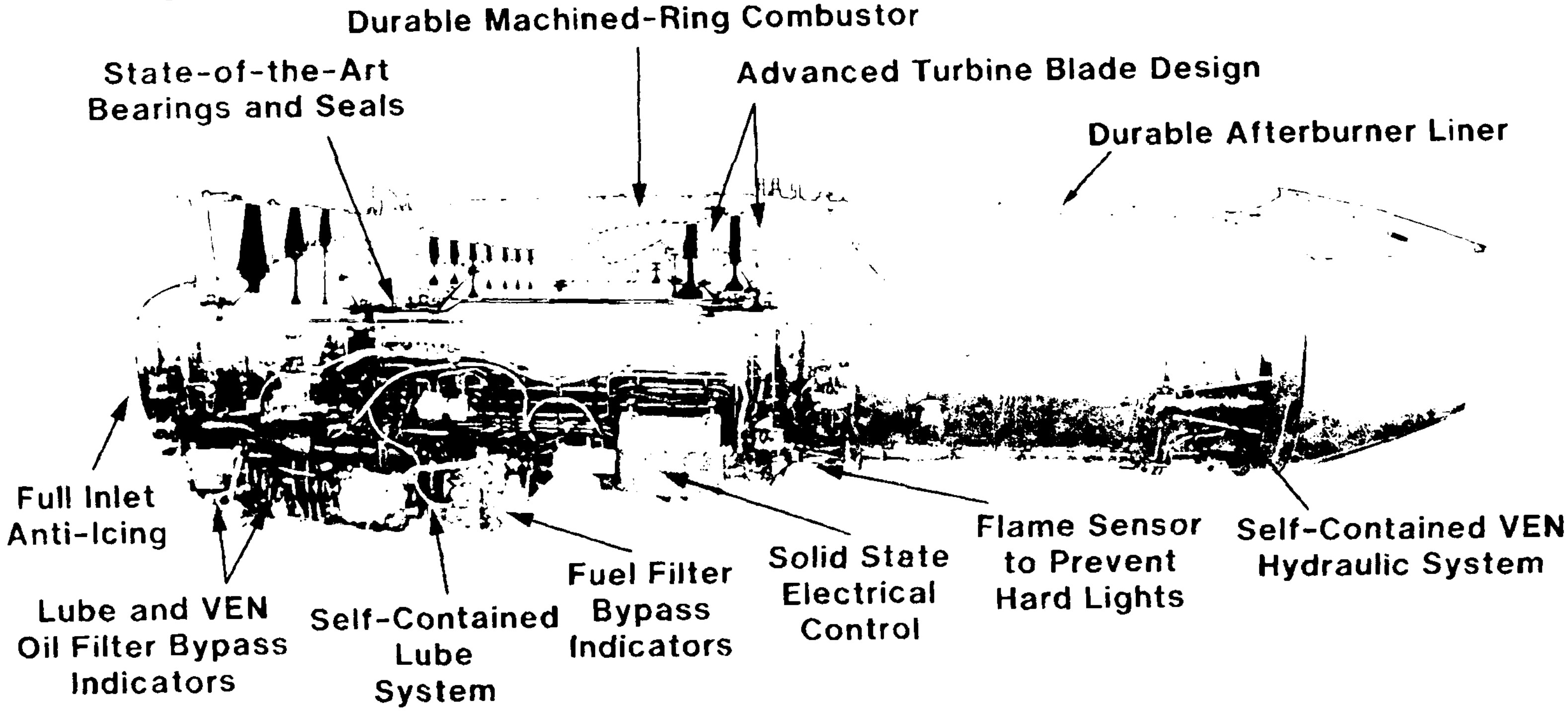
Most Important

- Operational Suitability
- Reliability
- Maintainability
- Cost
- Performance
- Weight

FIG. 7

F404-400 Reliability Features

Disciplined Test-and-Fix Program During Development

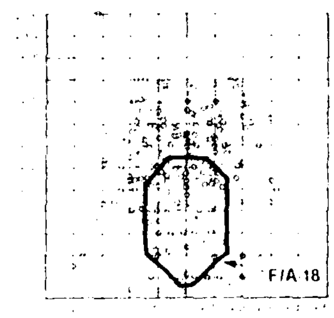


- Corrosion Resistance
- Demonstrated Rotor Containment
- All Casings Pressure-Tested
- All Components Fire-Tested
- Overspeed/Overtemperature Protection

FIG. 8

Operation Compatibility

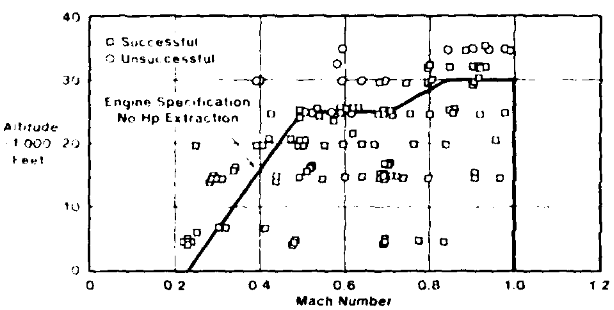
F/A-18 Maneuvering Experience



- Mach .15-.4
- 35-40,000 Feet
- Aircraft No. 6
- Outstanding Inlet Compatibility

Spooldown Airstarts

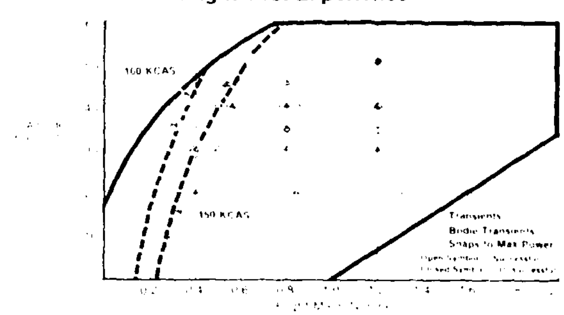
Aircraft



Engine Exceeds Specification

F/A-18/F404 Afterburner Operation

Flight Test Experience



Successful A/B Lights Throughout Envelope

FIG. 9

Rotor "Lead the Fleet" Plan

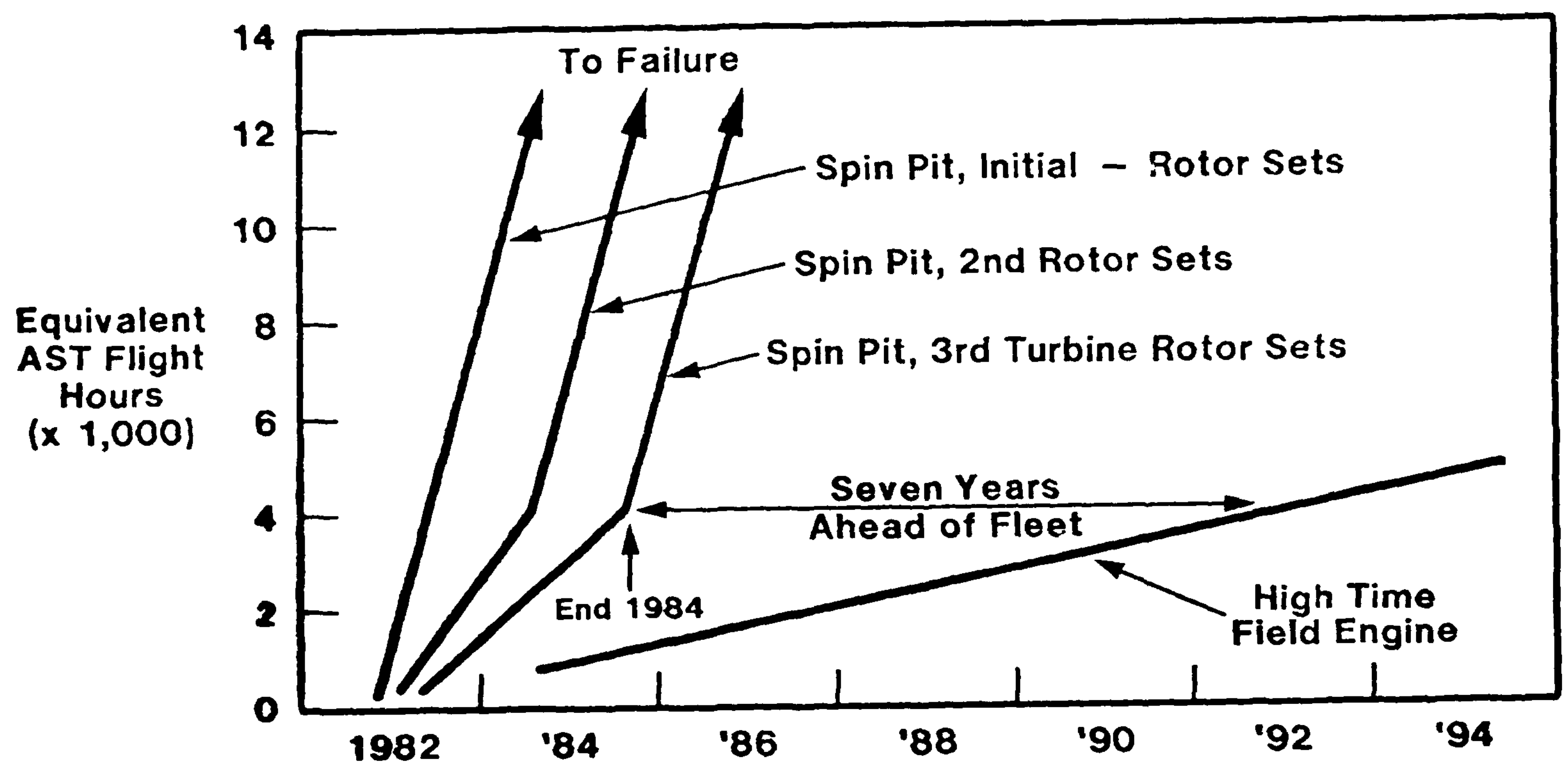
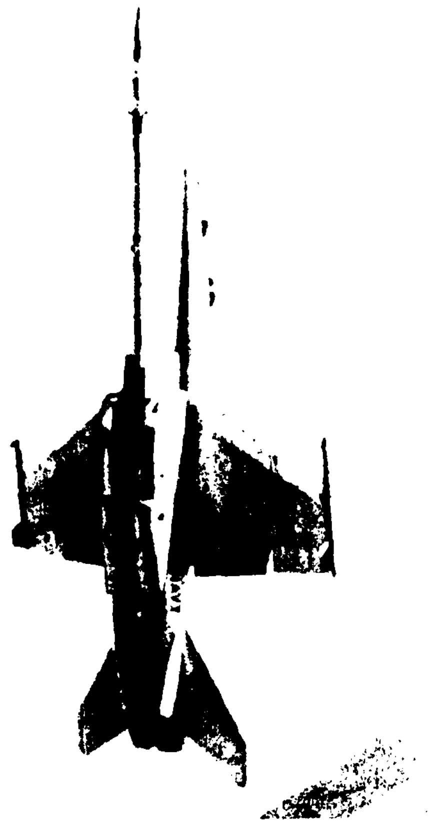


FIG. 10

Program Status



- USN/USMC Operational Sites
  - — Lemoore NAS
  - — Pt. Mugu NAS
  - — China Lake NWC
  - — El Toro MCAS
- CAF Operational Site
  - — Cold Lake
- Over 170,000 EFH
- Over 600 Production Engines Shipped
- High Time Engine 926 EFH
- Production Fleet Engine Average Age
  - — USN — 369 EFH
  - — Canada — 179 EFH

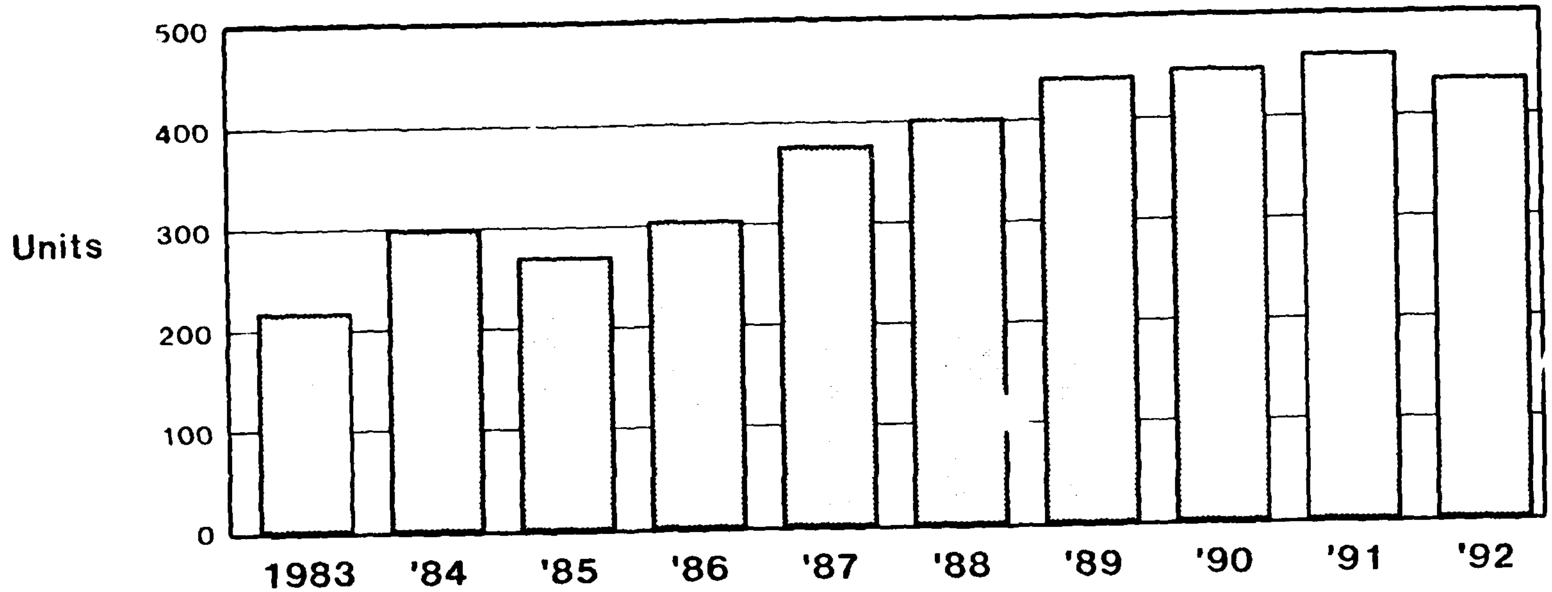
FIG. 11

F404 Status

- Over 550 Engines Shipped Since December 1979
  - 96 Percent First Run Acceptance Rate
- Currently Tooled For 26/Month Rate
- Over 160,000 F/A-18 Engine Flight Hours
- Reliability . . . Better Than Goal
  - 281 MTBF Versus 264 Goal At 24,000 Fleet Engine Flight Hours
- No Trim Verified
  - Engine Change
  - Module/Component Change

FIG. 12

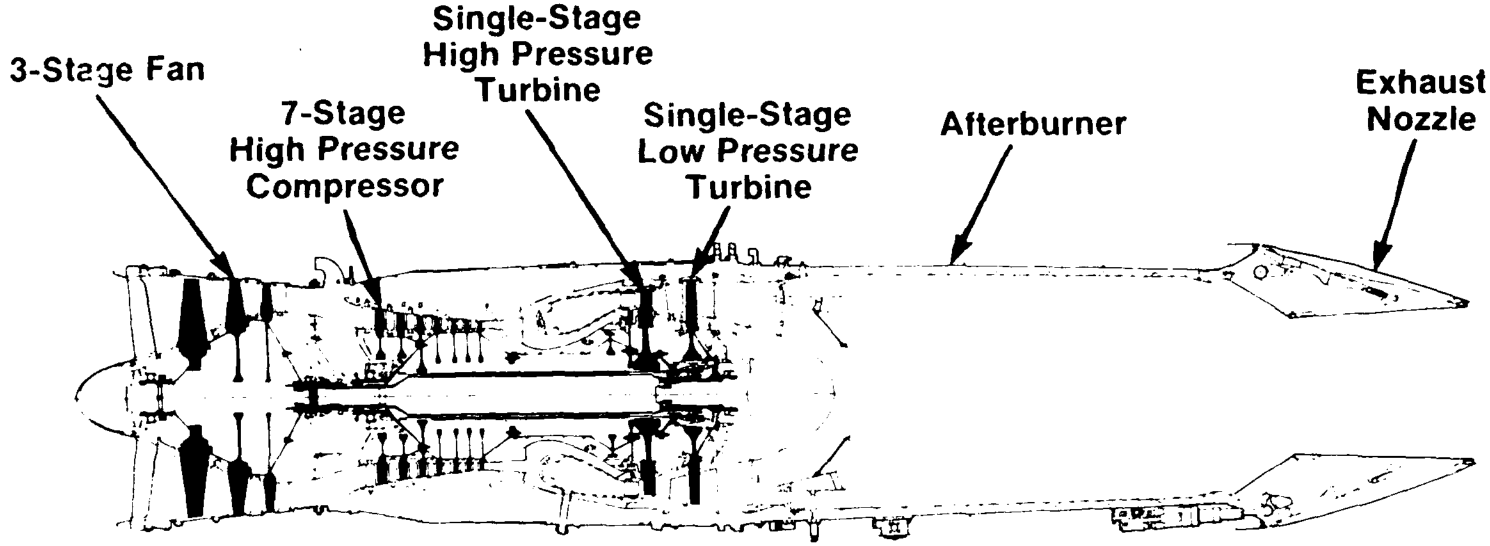
F404 Production Plan



- Performance Margin — Thrust 3%
  — SFC 2%
- Weight Margin — 23 Lb
- Production Engine Cost (Constant Dollars) Reduced By 34% — 1981 To 1984

FIG. 13

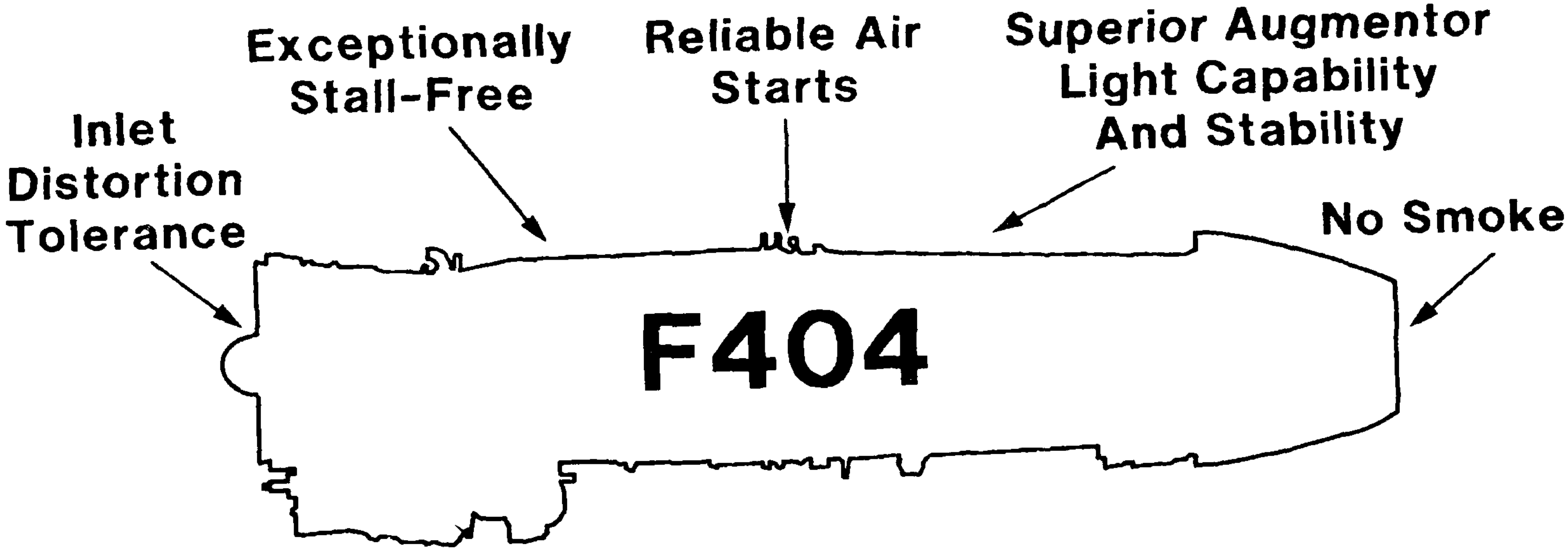
F404-GE-400



- 142 lb/sec Airflow
- 0.34 Bypass Ratio
- 7.5 Thrust/Weight Ratio Class

FIG. 14

The Fighter Turbofan With Turbojet Characteristics

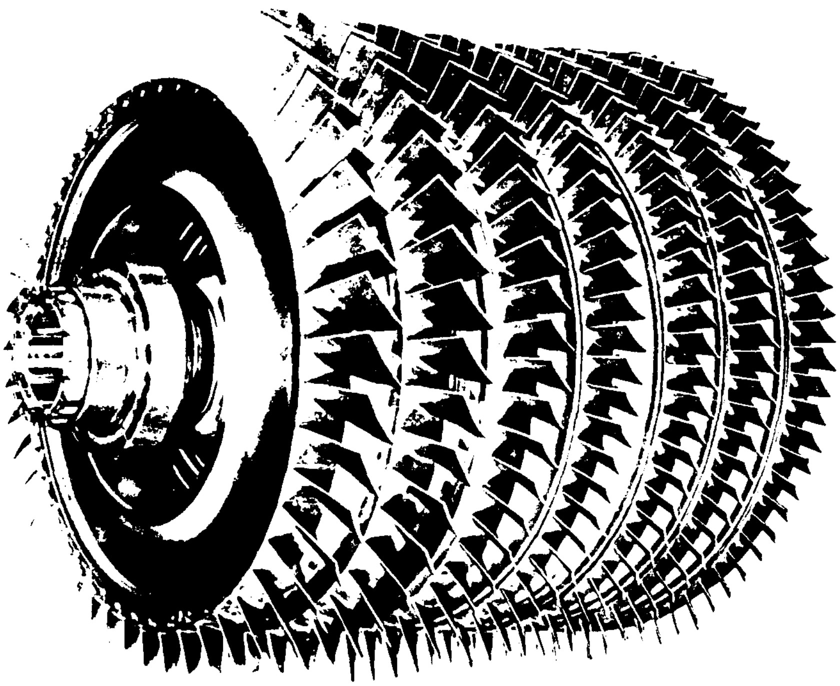


No Throttle Restrictions
<4 Seconds Acceleration
(Idle To IRP)

- High Thrust Without Afterburner
  - Supersonic Capability
  - Low Combat SFC

FIG. 15

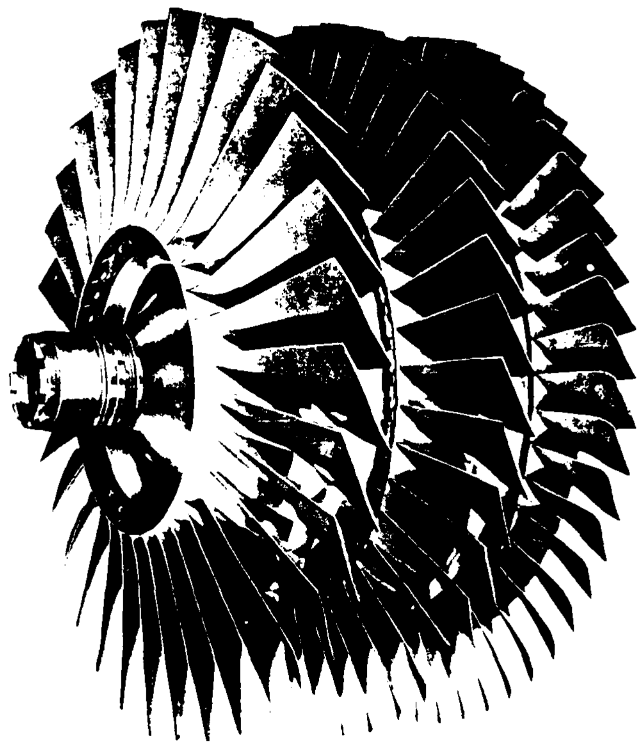
Compressor



Inertia Welded
Pressure Ratio 6.3:1

FIG. 16

Fan



Pressure Ratio 4:1

FIG. 17

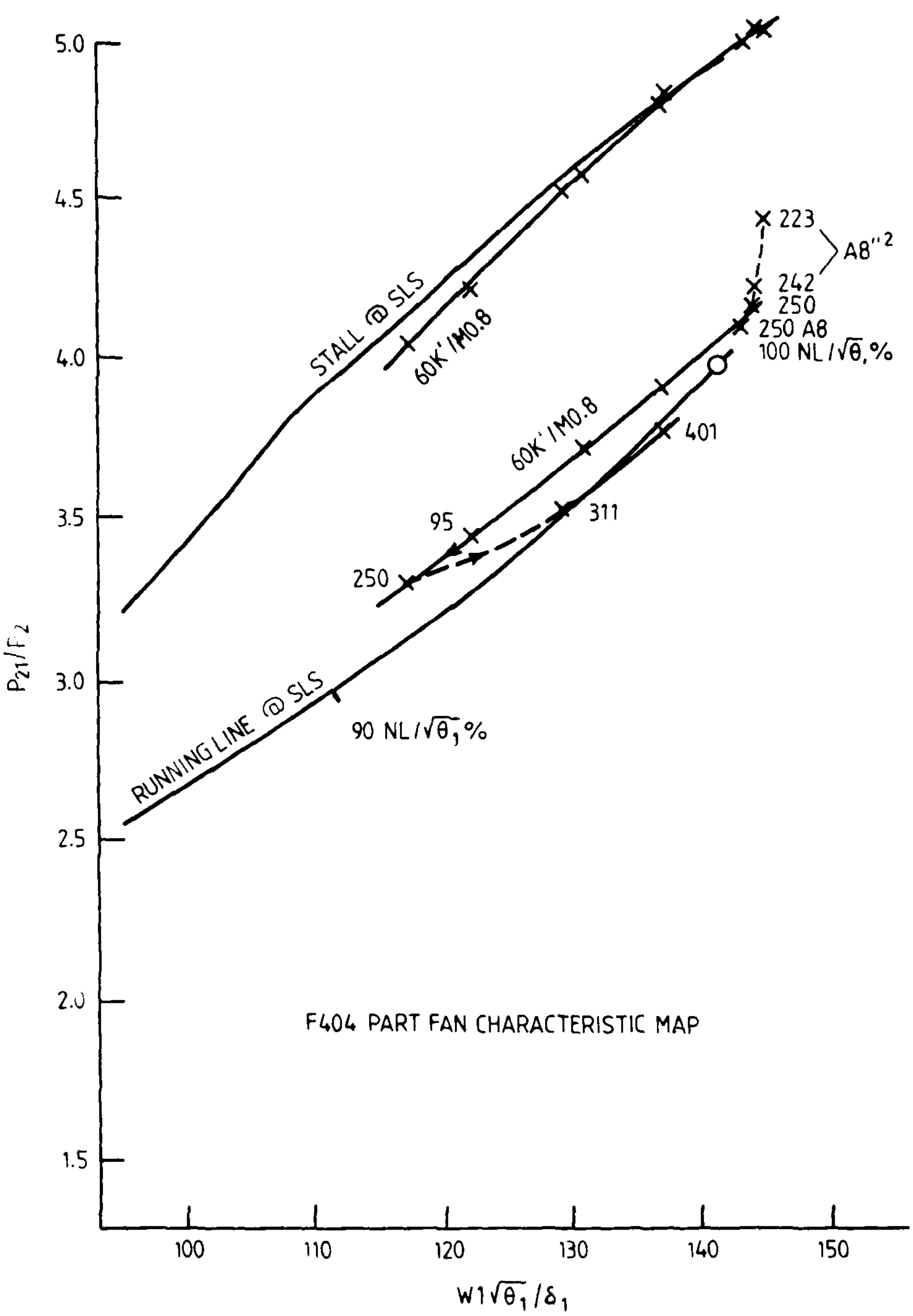
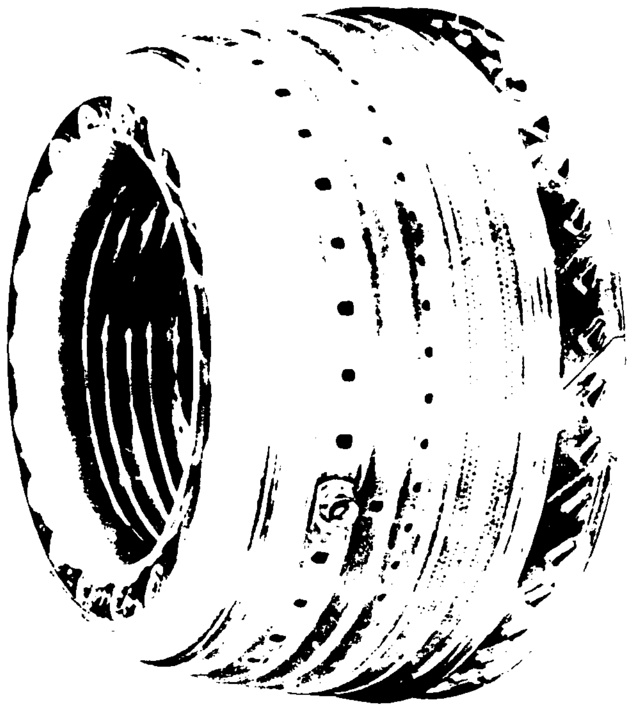

5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
P_{21}/P_2
100
110
120
130
140
150
$W1\sqrt{\theta_1}/\delta_1$
STALL @ SLS
60K'/M0.8
223
242
250
250 A8
A8"2
100 NL/√θ,%
60K'/M0.8
401
95
311
250
RUNNING LINE @ SLS
90 NL/√θ,%
F404 PART FAN CHARACTERISTIC MAP

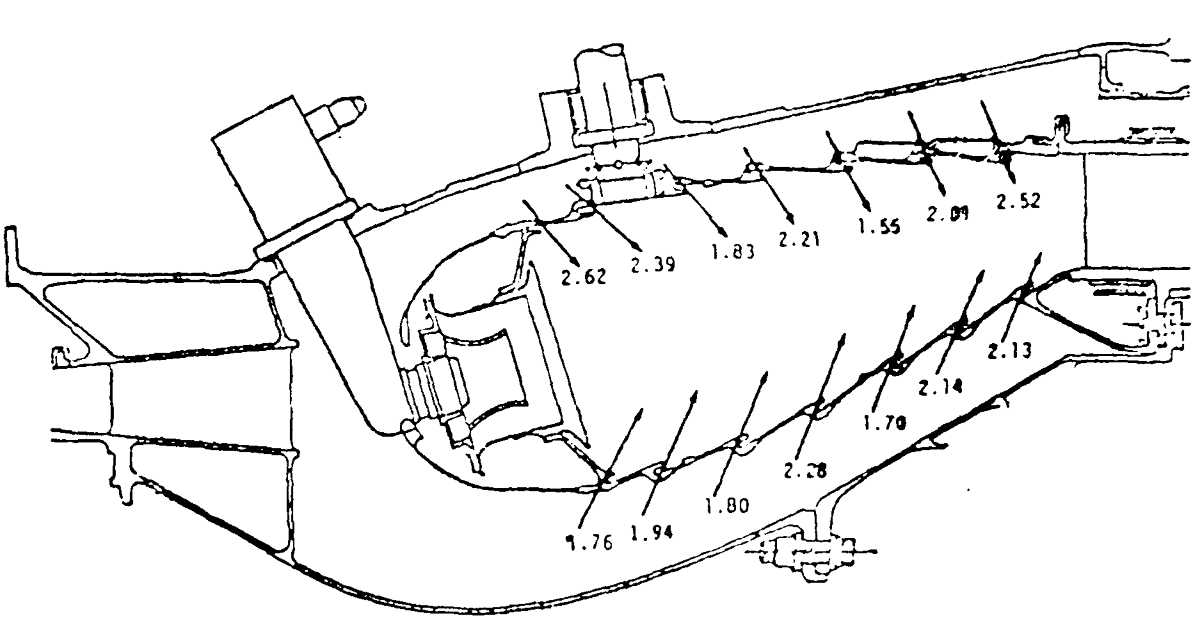
FIG. 18

Combustor



- Machined Ring
- Low Pattern Factor

FIG. 19

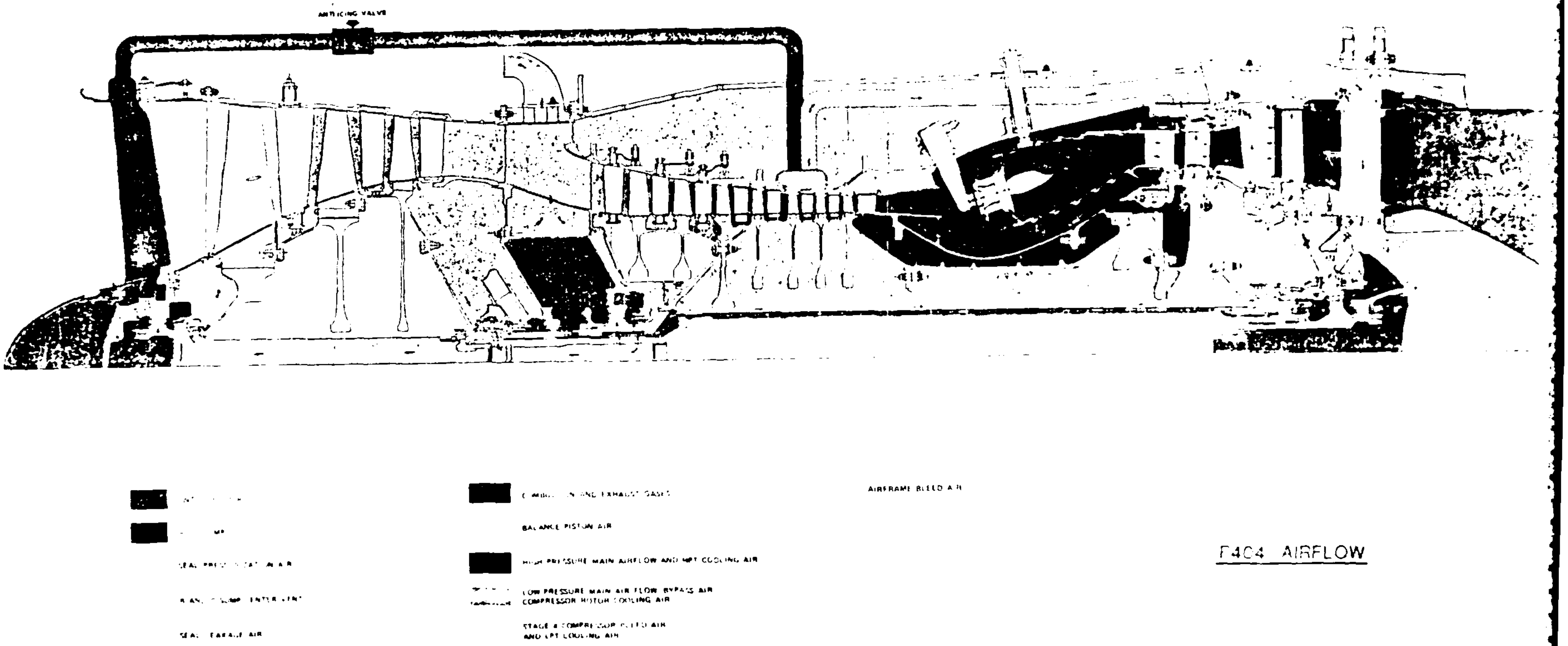


W_3 = #M/SEC

LINER SHELL COOLING FLOWS - % Wa 3.0

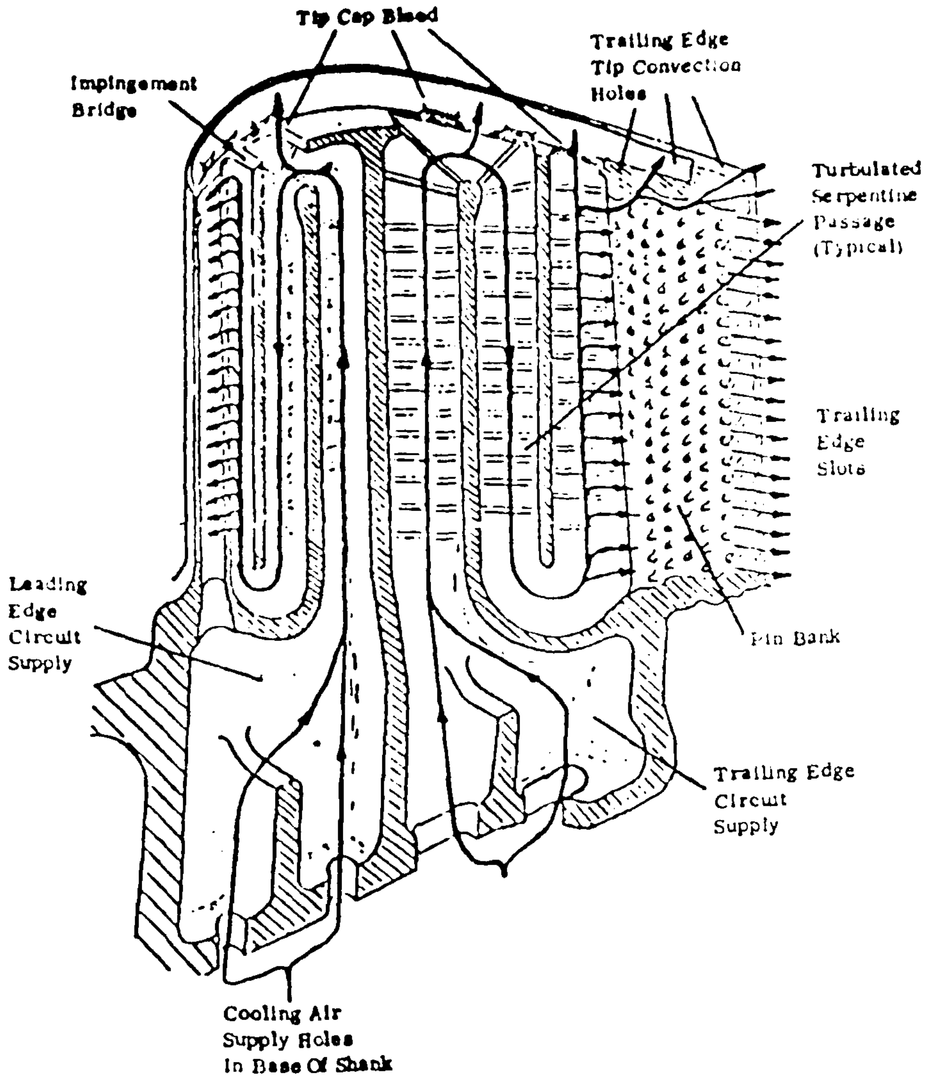
QT CONFIGURATION

FIG. 20



F404 AIRFLOW

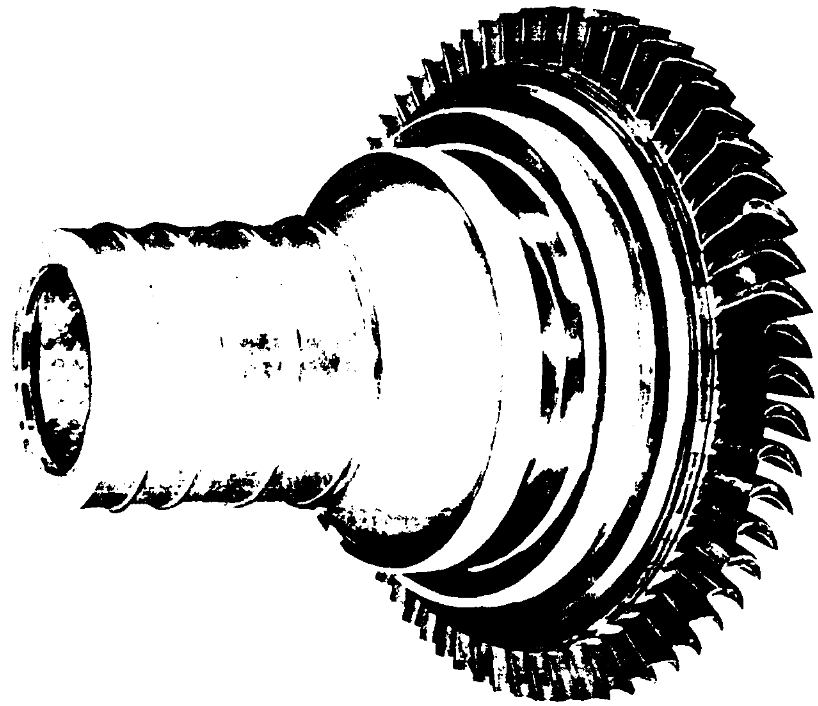
FIG. 21



Cutaway Schematic of HPT Blade Cooling System

FIG. 22

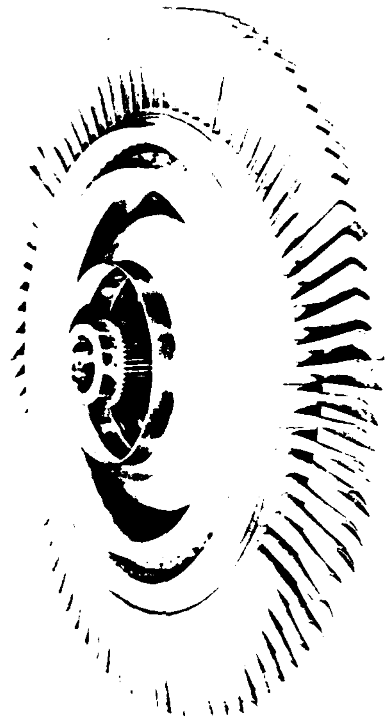
High Pressure Turbine



- Single Stage

FIG. 23

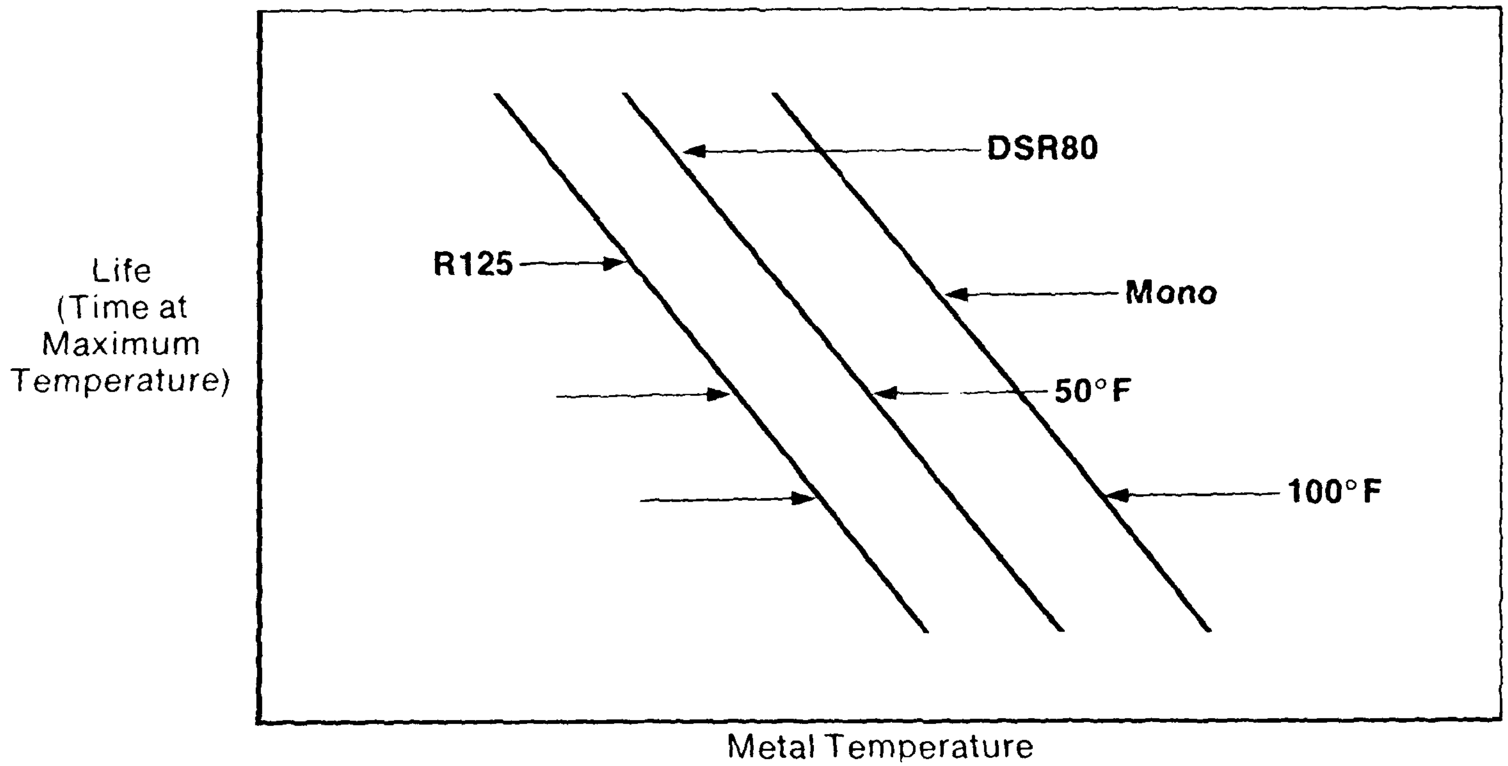
Low Pressure Turbine



- **Single Stage**

FIG. 24

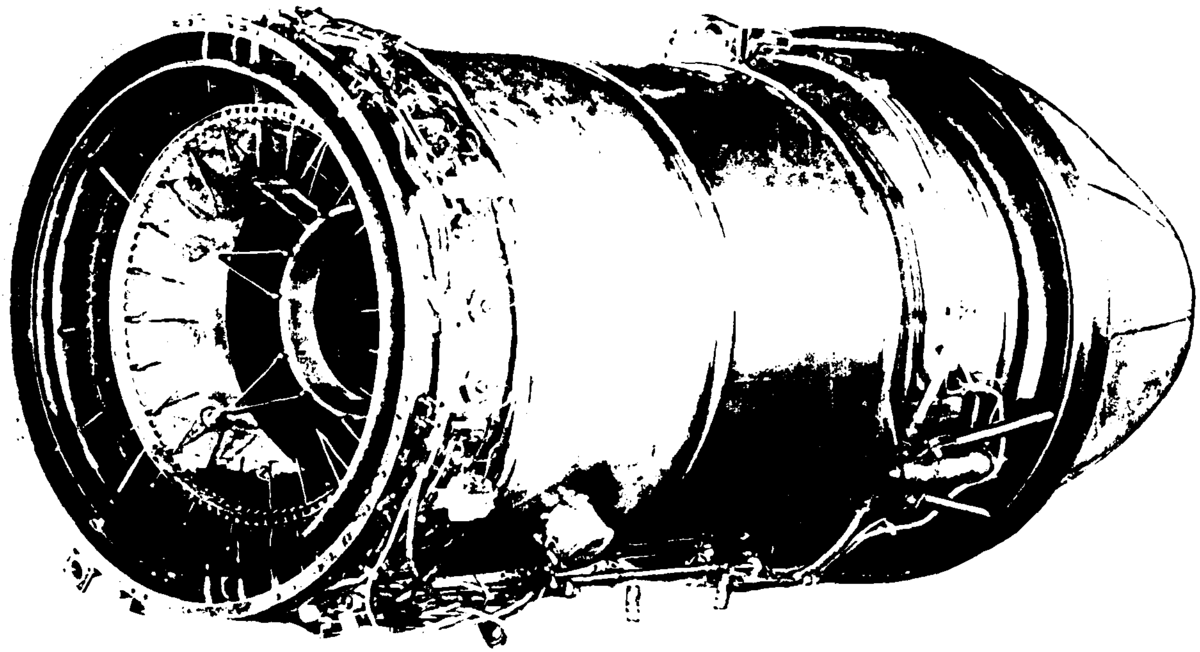
Typical Life/Temperature Characteristic



Hot Section Life is Sustained by Advancing Material Technology

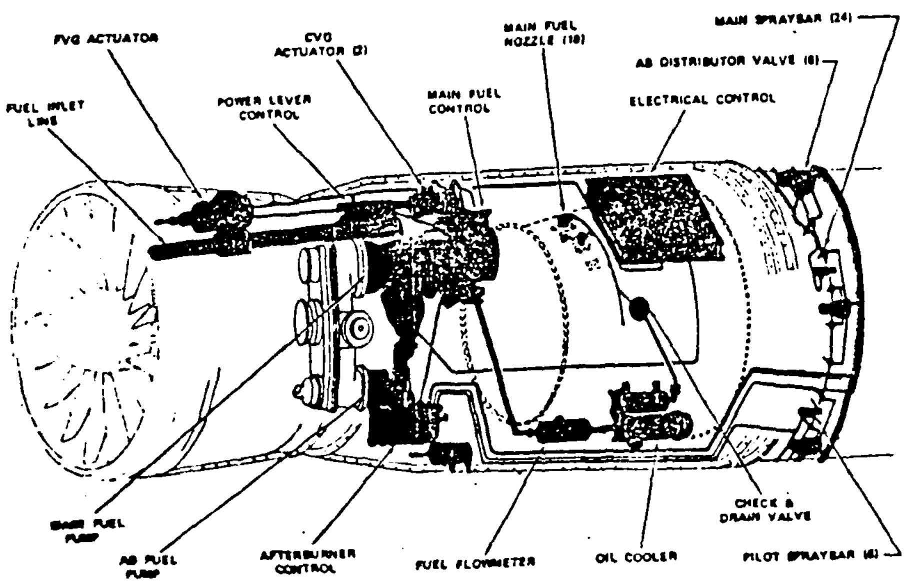
FIG. 25

Afterburner



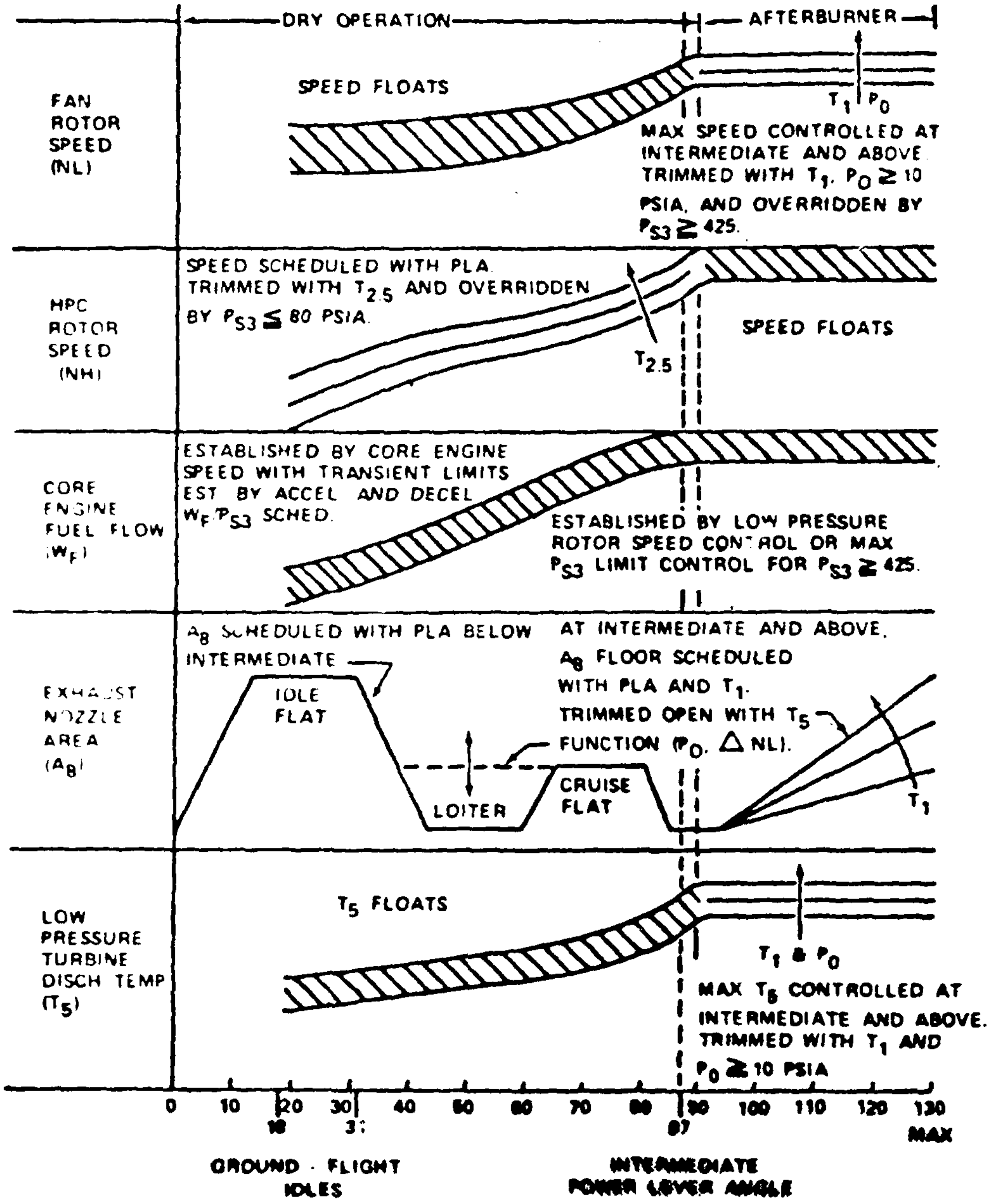
- 2-Stage Mixed Flow
- Soft Light-Off

FIG. 26



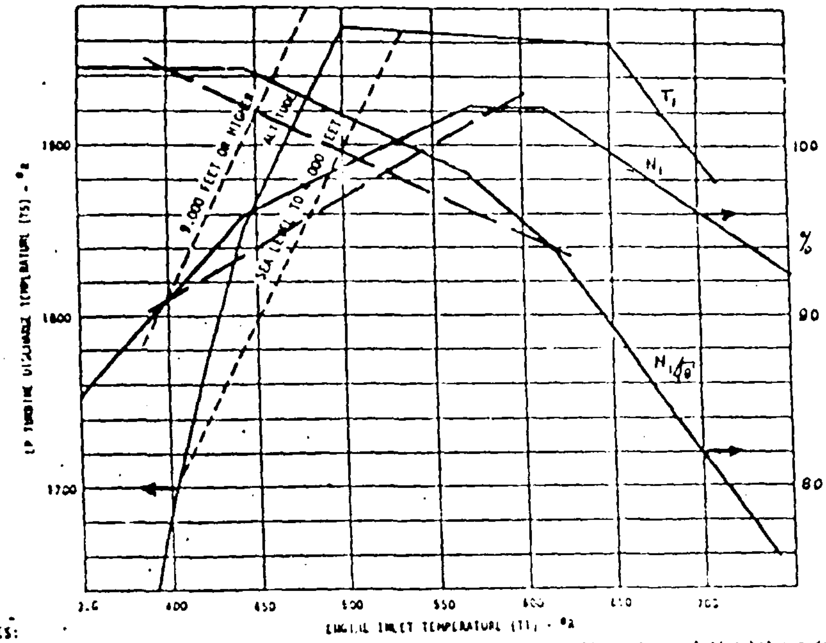
FUEL SYSTEM COMPONENTS

FIG. 27



CONTROL OPERATING MODES

FIG. 28



NOTES:

(1) Between 4,000 and 9,000 feet (Pressure Altitude), T5 is determined by linear interpolation between dash lines up to the solid line.

(2) Exact values at any condition T1 can be obtained from the specification computer

(3) Turbine discharge temperature is reset as a function of core engine fuel flow

FIG. 29

F404 Structures

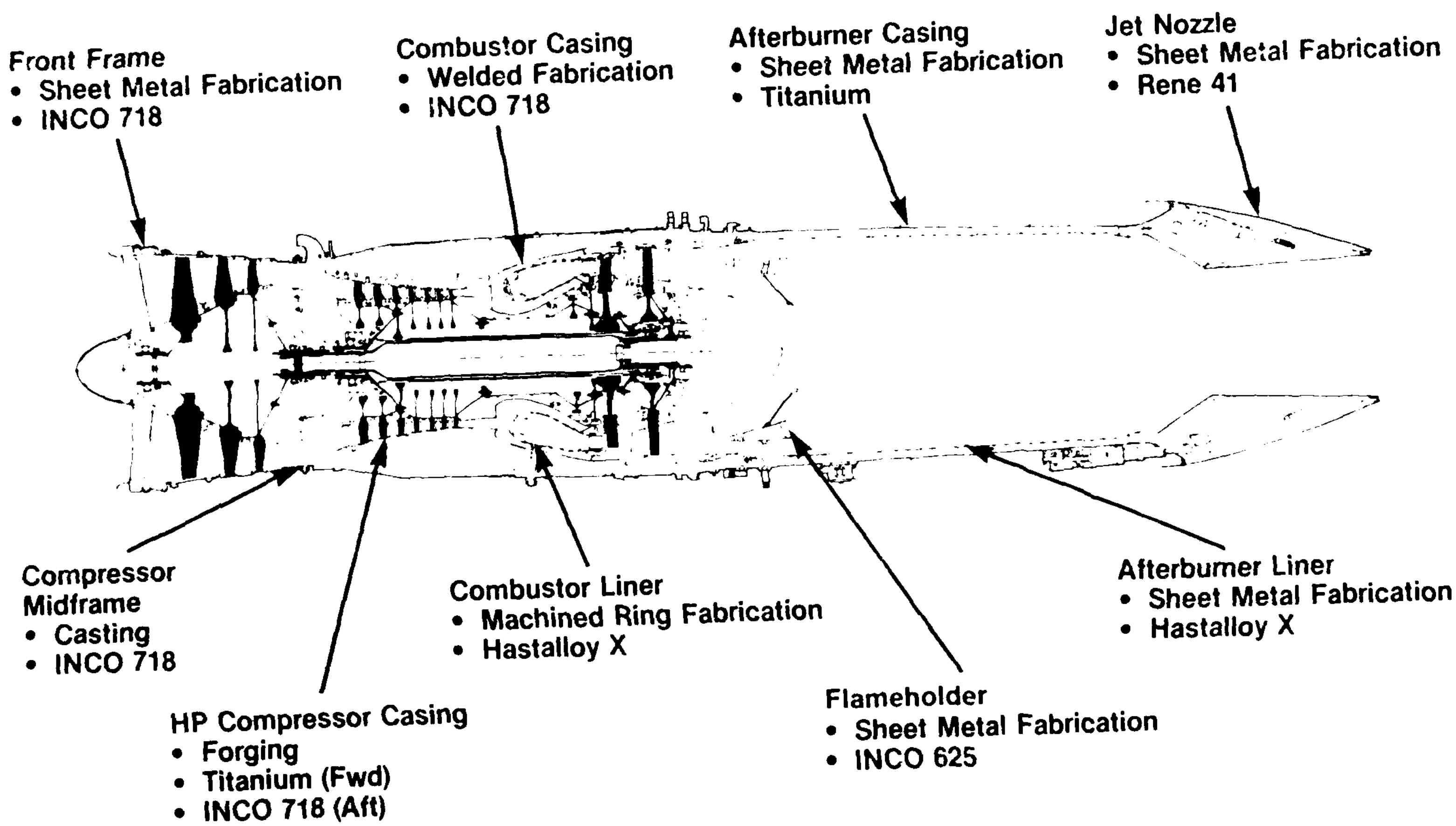


FIG. 30

F404 Turbomachinery

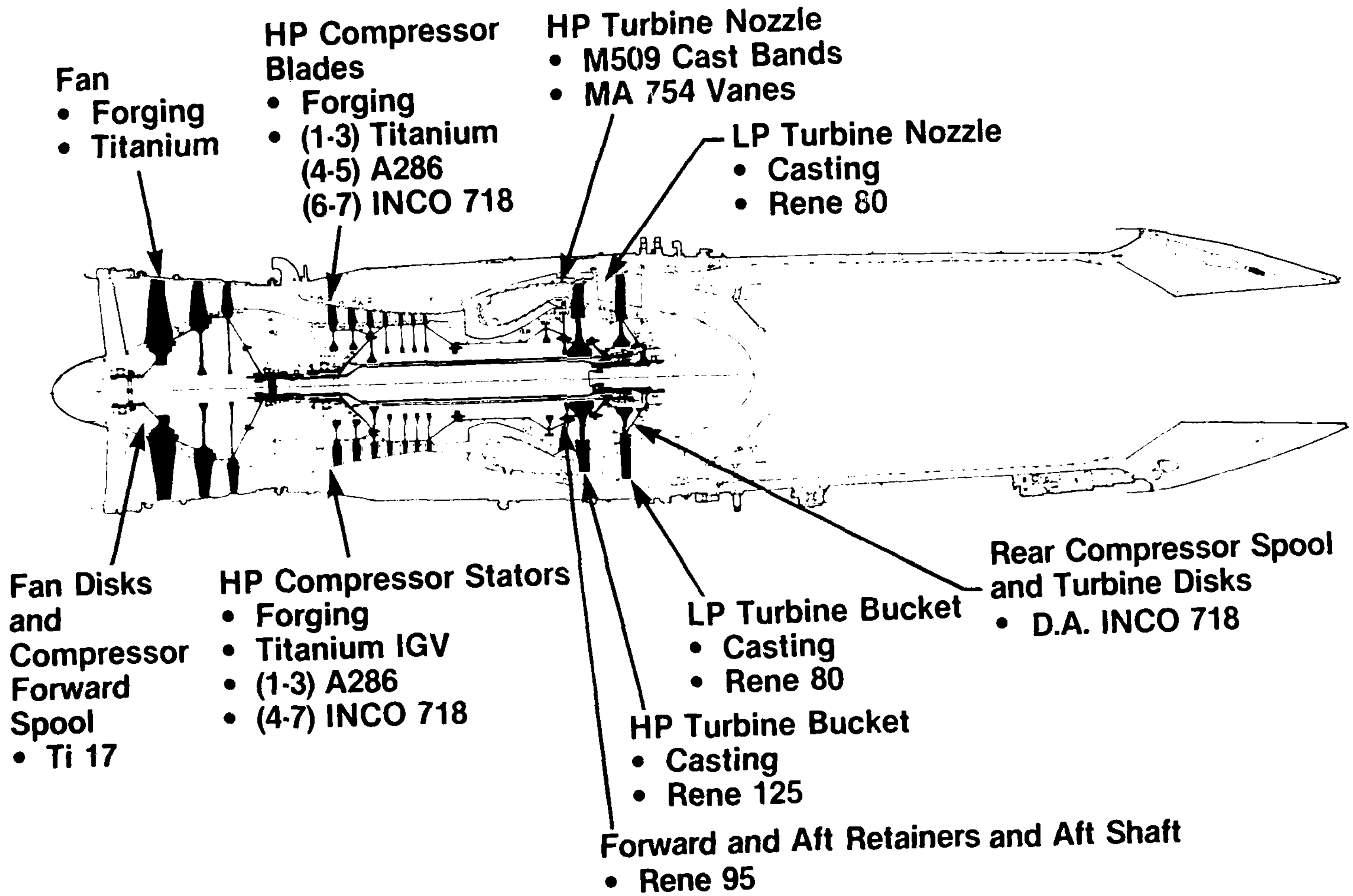


FIG. 31

Excellent Operability

- **A Turbofan with Turbojet Characteristics**
  - — High Combat Thrust without Lighting the Afterburner
    - Saves Fuel — Longer Mission Capability
  - — Stall-Free Operation Throughout Flight Envelope
    - Rocket/Gun Firings
    - Extreme Aircraft Maneuvers
    - Outstanding Inlet Compatibility
  - — Unrestricted Throttle Movements Throughout Flight Envelope
  - — Rapid Acceleration/Deceleration

A Fighter Pilot's Engine

FIG. 32

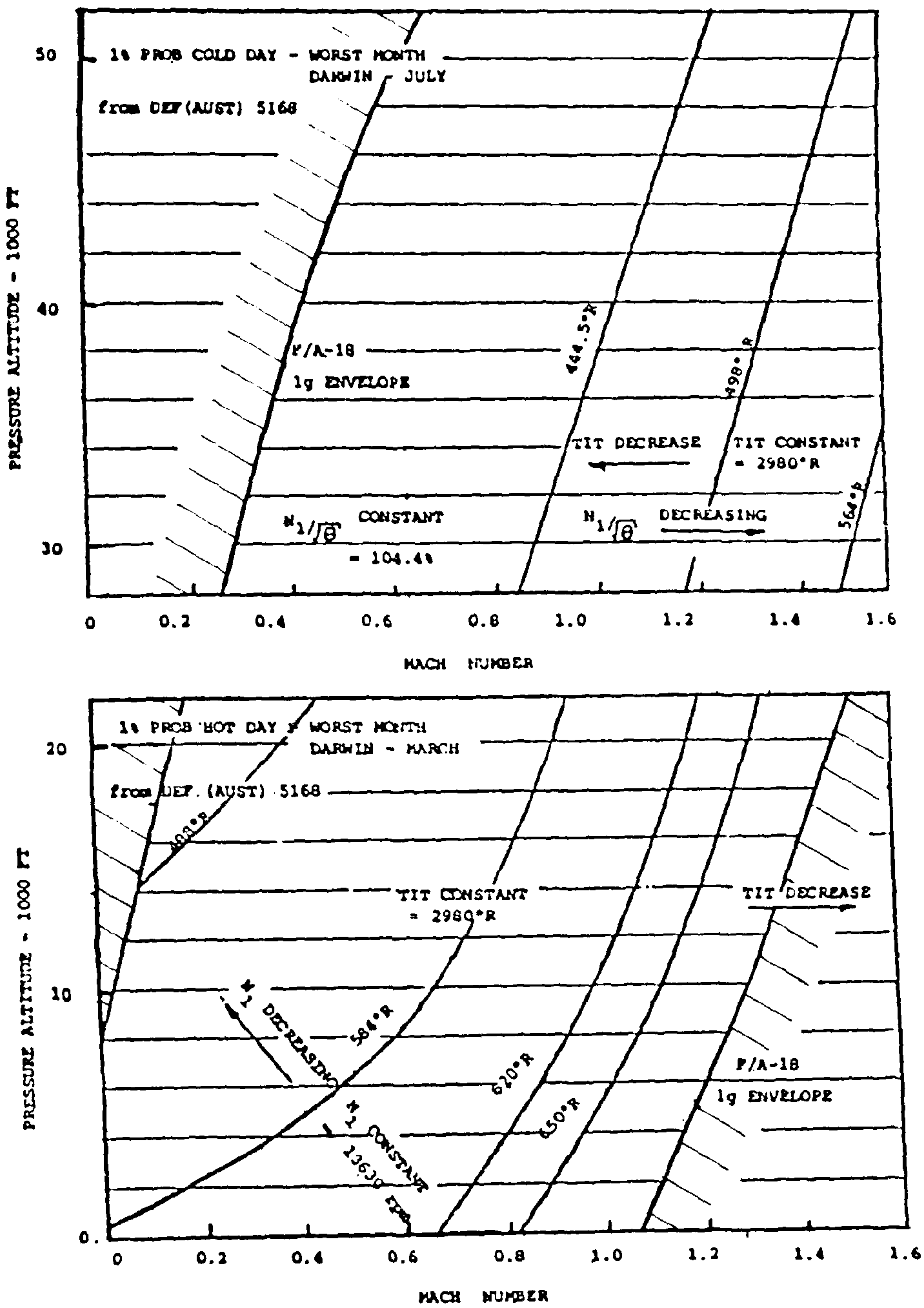

1% PROB COLD DAY - WORST MONTH
DARWIN - JULY
from DEF(AUST) 5168
F/A-18
1g ENVELOPE
444.5°R
498°R
564°R
TIT DECREASE
TIT CONSTANT
= 2980°R
CONSTANT
= 104.4%
DECREASING
PRESSURE ALTITUDE - 1000 FT
MACH NUMBER
1% PROB HOT DAY - WORST MONTH
DARWIN - MARCH
from DEF. (AUST) 5168
TIT CONSTANT
= 2980°R
TIT DECREASE
584°R
620°R
650°R
F/A-18
1g ENVELOPE
PRESSURE ALTITUDE - 1000 FT
MACH NUMBER

FIG. 33

“On-Condition” — Definition

“On-Condition” is directed at a **specific** unit (e.g., engine S/N XXX) in order to determine the “health” of **that** unit. The philosophy of On-Condition is to allow the life of a unit to be determined by the condition of the unit in comparison with a pre-determined standard, instead of some arbitrary hour limitation. It is “before-the-fact” maintenance.

FIG. 34

IECMS

IN-FLIGHT ENGINE CONDITION MONITORING SYSTEM

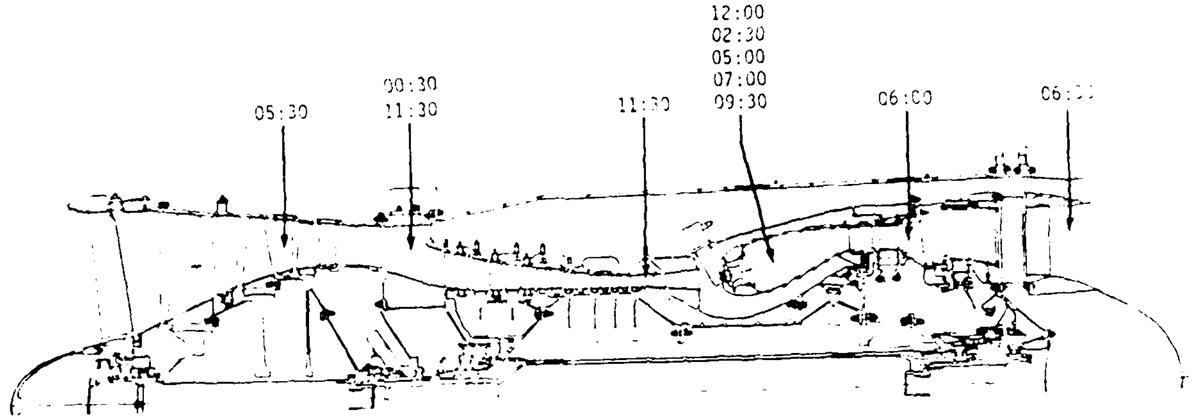
RECORDS FOR POST-FLIGHT ANALYSIS

- LIFE USAGE INDICATORS
- MALFUNCTION INDICATORS
- PRE-POST EVENT RECORD
- PERFORMANCE TREND RECORD

+

- FLIGHT INCIDENT RECORD

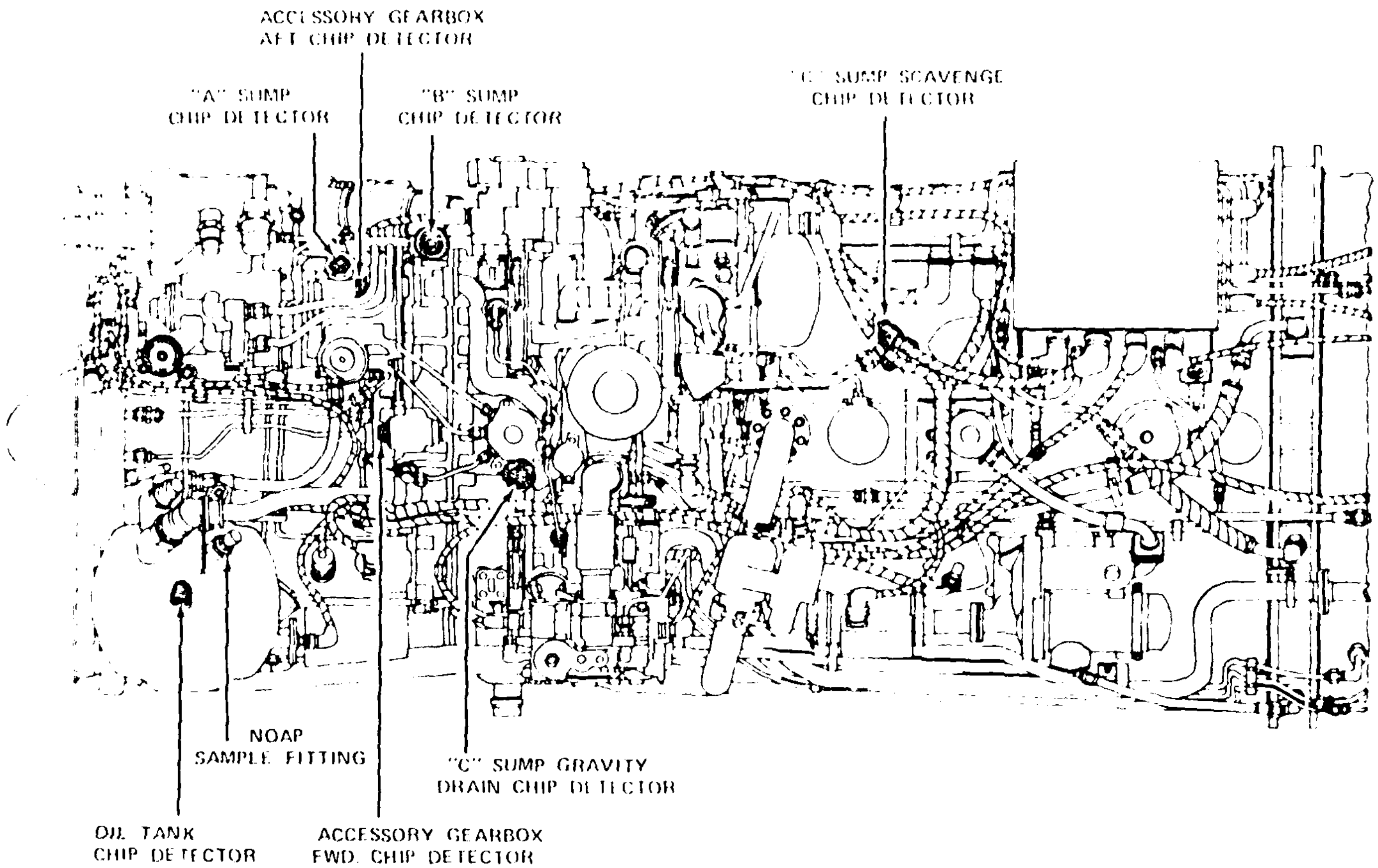
FIG. 35



CLOCK POSITIONS,
AFT LOOKING FORWARD

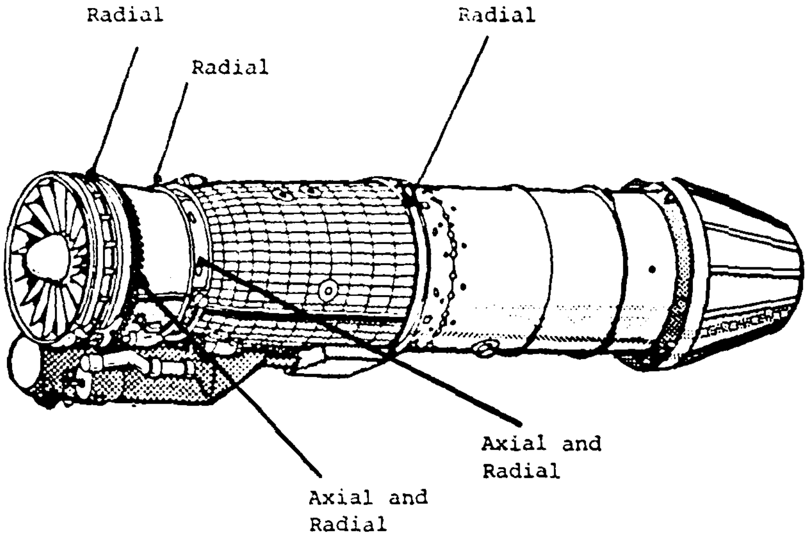
BORESCOPE PORT LOCATION

FIG. 36



CHIP DETECTOR LOCATIONS

FIG. 37



NOTE : ECMS and a
Mount-ring accelerometer
are on the starboard
side.

F - 404 ENGINE : ACCELEROMETER LOCATIONS (ARL TEST)

FIG. 38

Advantages Of Modular Program

- **Improved Aircraft Readiness Rate**
  - Reduced Shop Turnaround Time
  - No Aircraft "Open Hole" During Module Repair Cycle
- **Reduced Spare Engine Requirements**
  - Module Procurement Substitutes For Engine Procurement
  - Reduced Engine Pipelines
- **Ratio Of Modules Optimized**
  - Module Levels Procured Can Conform To Reliability Achieved For Each Module (MTBR)

FIG. 39

F404 Engine Modules

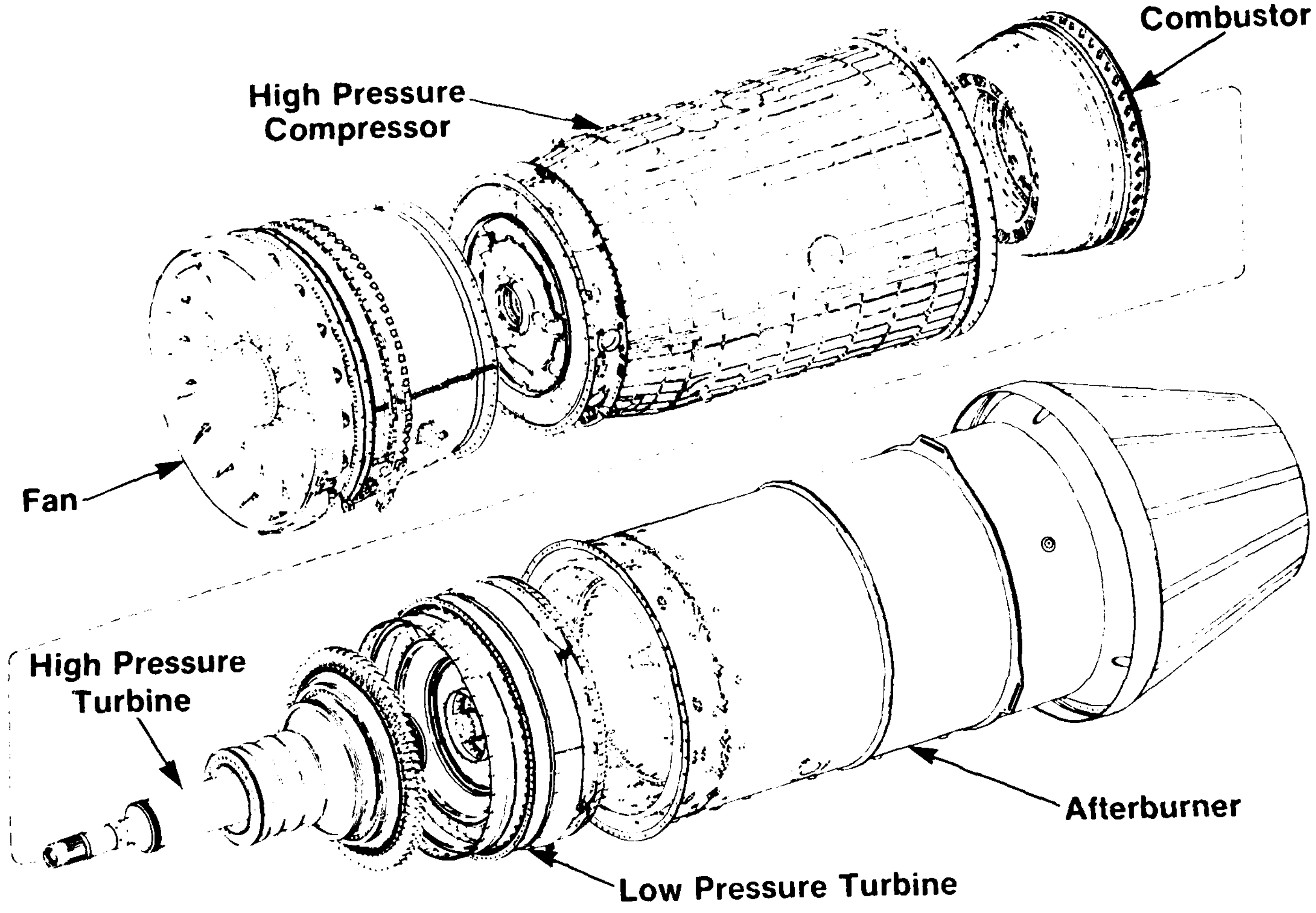


FIG. 40

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Turbofan engines F404-GE-400 engine F/A-18 aircraft	21050

16. Abstract

The F404 engine in the F/A-18 is representative of a new generation of military turbofan engines. The features of the engine that govern its performance and contribute to its maintainability are discussed. The intention is to give the non-specialist an appreciation of those factors materially affecting the operation of this type of engine.

PF 65

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